Time critical Industrial IoT: Cross-Layer design for Prioritized and Multi-hop Medium Access

By
Syed Fahad Hassan
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Supervisor
Dr. Syed Ali Hassan
Department of Electrical Engineering

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Approval

It is certified that the contents and form of the thesis entitled "**Time critical Industrial IoT: Cross-Layer design for Prioritized and Multi-hop Medium Access**" submitted by **Syed Fahad Hassan** have been found satisfactory for the requirement of the degree.

Advisor: **Dr. Syed Ali Hassan**
Signature: __________________

Date: __________________

Committee Member 1: **Dr. Fahd Ahmed Khan**

Signature: __________________
Date: __________________

Committee Member 2: **Dr. Sajid Saleem**

Signature: __________________
Date: __________________

Committee Member 3: **Dr. Salman Abdul Ghafoor**

Signature: __________________
Date: __________________

Abstract

Wireless technologies are nowadays being considered for implementation in industrial automation. However due to strict reliability and timeliness requirements of time-critical applications, there are many open research challenges for the merger of wireless technologies with the industrial systems. Although many medium access and control (MAC) protocols are proposed in recent years, a coherent effort on both the physical and MAC is needed. In this paper, we propose a protocol termed as multiple equi-priority MAC (MEP-MAC) which combines the functions of MAC and physical layers: the MAC layer ensures a deterministic behavior of the system by assigning priorities to the nodes, while non-orthogonal multiple access (NOMA) at the physical layer enables multiple nodes of equal priorities to simultaneously gain the channel access and transmit data to the gateway. We adapt a discrete-time Markov chain (DTMC) model to handle multiple nodes of equal priorities and perform the analytical analysis of the proposed protocol. The results show that the proposed protocol can provide upto 70% and 40% improvement in terms of system throughput and latency respectively as compared to a system that does not leverage NOMA at the physical layer. We then extend our work for a multi-hop scenario in which not all nodes are in vicinity of the gateway. Such nodes leverage multi-hop to transmit their data to the gateway. We modify the DTMC to model this multi-hop scenario and perform the analytical analysis in terms of system throughput and worst-case latency.

Dedication

I dedicate this thesis to my father, **Syed Tanweer Hasan** and my mother, **Shehla Tanweer**. Without their constant prayers, this day might never have come.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

Author Name: **Syed Fahad Hassan**

Signature: ____________________

Acknowledgment

I would like to thank Allah Almighty for His blessings on me to carry out this research work. Secondly, I would like to extend my gratitude to my advisor, Dr. Syed Ali Hassan, for his constant support throughout my research. Finally, I would like to thank my most supportive, understanding and dedicated parents as without their encouragement and guidance, I would not have been able to achieve what I have thus far.

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Chapter 1

Introduction To Thesis

1.1 Internet of Things

The concept of Internet of Things (IoT) has become a hot topic for research in recent years. It involves billions of heterogeneous devices communicating with each other. IoT will empower such devices with many new capabilities [2–4]. It will equip objects of everyday use with capabilities of identification, sensing, processing and networking. Ultimately, IoT enables devices are context-aware [5–7], intelligent [8, 9] and ubiquitous [10–12].

The concept of IoT is not new. The use of technologies such as wireless sensor networks [13] and RFID in industrial and manufacturing fields [14] has been around for a long time. The concept of machine-to-machine (M2M) communication [15, 16] is also common, as it is one of the main concepts of internet where servers and clients communicate with each other without any constant human intervention. IoT, however, is the evolution of these technologies in terms of number and type of devices as well as interconnection

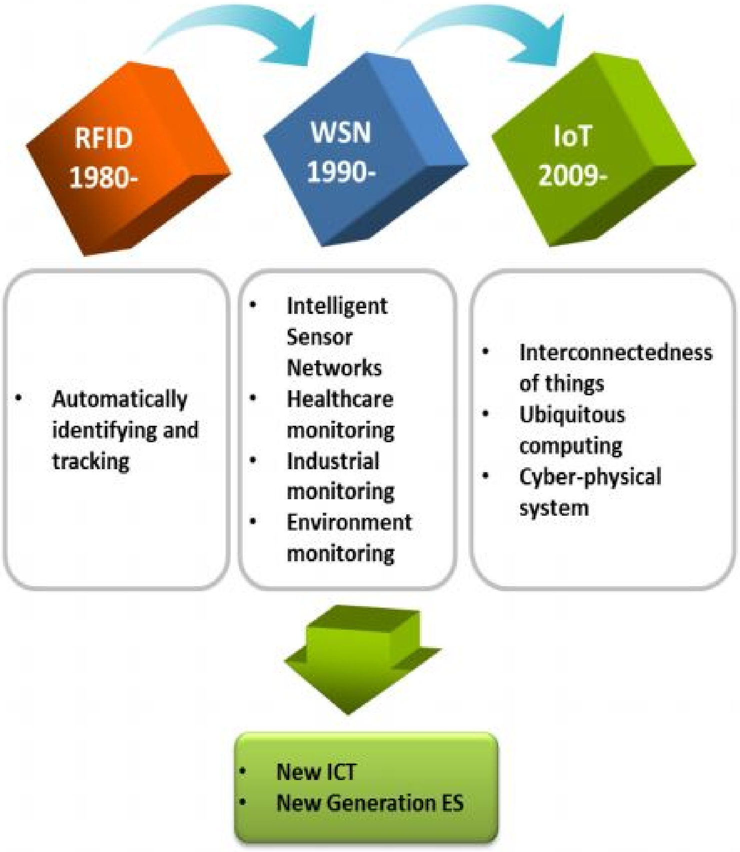

Figure 1.1: The evolution of IoT related technologies

between networks of such devices. Figure 1.1 RFID has mainly been limited to industrial domain and M2M communication has been limited to computing devices such as servers, desktops, laptops and smartphones etc. IoT proposes to attach technology to objects of everyday use such as home appliances, medical appliances, agricultural appliances, which were not designed to be intelligent. Moreover, IoT also proposes to interconnect such devices over the internet. For example, RFID was used to track the products through certain phases of the supply chain. However, the product tracking was not possible as it left the retail store. IoT promises to enable traceability of the product throughout its entire lifecycle by connecting it over the internet. [1] shows how the IoT related technology has evolved over the years.

1.2 Thesis Contribution

Main contributions of this thesis are listed below:

- This thesis presents a new cross-layer protocol termed Multiple Equi-Priority MAC (MEP-MAC), which combines the functions of physical and MAC layers to ensure real-time performance.
- To this end, we develop a stochastic theoretical model which can be utilized to analyze the performance of the system in terms of system throughput and latency. Furthermore, we also analyze how the performance of our proposal is impacted under non-ideal physical conditions.
- We also carry our research work for Multi-Hop network, in which not all nodes can directly communicate with the central gateway. Such nodes then leverage multi-hop communication and forward their data to another node, which can directly reach the gateway. That node then relays information to the gateway.
- We develop a theoretical stochastic model for multi-hop communication to analyze the performance in terms of system throughput and worst-case latency.

1.3 Structure of the Thesis

The rest of the thesis as organised as follows. Chapter 2 provides the literature review for concepts on which this thesis is based, which include Internet of Things (IoT), industrial automation and Non Orthogonal Multiple Access (NOMA). Chapter 3 discusses the MEP-MAC protocol. For the system model, we develop a Discrete Time Markov Chain (DTMC) using which we form equations for transition and steady-state probabilities. These probabilities are then used for mathematical analysis in terms of system throughput and worst-case latency. In Chapter 4, we discuss communication of nodes with the central gateway in a multi-hop scenario where not all nodes are in a reachable distance from the gateway. Data from such nodes is sent to the gateway via multi-hop. For the system model, we modify the DTMC model for the multi-hop scenario, using which we form equations for transition and steady state probabilities. We then use these equations to analyze the system performance using parameters, which include system throughput and worst-case latency. The thesis is concluded in Chapter 5, with some future directions mentioned.

Chapter 2

Literature Review

2.1 Industrial IoT (IIoT)

The concept of IoT can be extended to industrial and manufacturing domain, and in recent years there has been growing interest in IoT for industrial applications [17]. Research on IIoT is still premature but there are many areas where it can be utilized such as environment monitoring, healthcare, production management, transportation, security & surveillance and Fast Moving Consumer Goods (FMCG) supply chain [18–21]. Some of the above mentioned use-cases of IIoT are discussed below.

In healthcare, many benefits can be reaped from the use of IoT. All the medical equipment and appliances can tracked and maintained relatively easily. As IoT devices are globally connected, all healthcare related information such as logistics, finance, therapy, medication, daily activity and diagnosis can be shared and maintained very easily [22–24]. The IoT based healthcare services can be personalized and mobile [25]. However, security and privacy still remain a challenge in this domain.

IIoT can help in simplifying a rather complex FMCG supply chain [26], which involves complex operations in quality management, operational efficiency and stakeholder management. The complete setup can be divided into three parts; field devices, infrastructure network and communication interfaces. As IoT offers ubiquitous networking, all the elements of the setup can be distributed and data obtained from every element can be mined and used for analytics. The IoT enables are also able to sense and process information which can be collected and used for analysis.

IoT can play a significant role in transport and logistics domain. In the logistics industry, more and more physical objects are equipped with RFID tags and sensors, which allows companies to track and monitor the product throughout the supply chain, which includes manufacturing, shipping and distribution [27]. IoT can also provide various promising solution for evolution of transportation services. This can include proper utilization of parking space, for vehicle tracking and monitoring and predicting its upcoming location based on the current route information. There has been a lot of research going on for driver-less cars. Companies such as Tesla and Google are spearheading the research in this domain and in a few years time, we may see driver-less cars on the road, which can automatically detect pedestrians and obstacles and take evasive maneuvers to avoid collisions.[28–30].

2.2 Non-Orthogonal Multiple Access (NOMA)

The NOMA technique allows the gateway to service multiple nodes at same time, frequency and code but different power levels. The gateway allocates higher power to the node having weaker channel conditions and lower power to the node with stronger channel conditions. The gateway then receives a superimposed signal and uses a technique known as successive interference cancellation (SIC) to decode the data of the nodes. It first decodes the data of the node which had stronger channel conditions and treats the data of the other node as noise. After successful decoding, this information is subtracted from the received superimposed signal to decode the data of the other node. [31–42]

Chapter 3

Wireless Mediation for Equi-Priority Nodes

In this chapter, we propose a protocol termed as multiple equi-priority MAC (MEP-MAC) which combines the functions of physical and MAC layers to ensure real-time performance. At the MAC layer, MEP-MAC ensures that a deterministic channel access is provided by prioritizing the channel access for every node. At the physical layer, it leverages the non-orthogonal multiple access (NOMA) technique [43], which allows more than one node to concurrently communicate with the central gateway in a transmission slot. As a result, multiple nodes having data of the same significance can be awarded simultaneous channel access. We develop a stochastic theoretical model for the proposed improvement which can be utilized to analyze the performance of the system in terms of throughput and latency. We show that the proposed protocol results in significant improvement in the system performance. Furthermore, we also analyze how the performance of our proposal is impacted

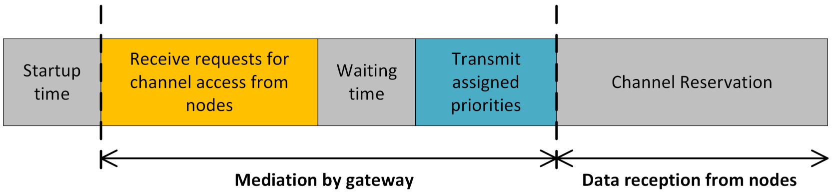

Figure 3.1: Mediation process as seen from the gateway

under non-ideal physical conditions.

3.1 System Model

Considering a centralized control mode is commonly in place in industrial applications, we assume a star topology in which the network nodes are connected to the central gateway. The network nodes can be industrial devices such as sensors and actuators. It is assumed that all the nodes are within a detection range of each other. Before any data transmission, each node transmits channel access request to the gateway on a pre-assigned orthogonal frequency. The gateway acts as a mediator and decides the channel access priority of each node. The node with the highest priority is granted channel access immediately while the remaining nodes wait for a deterministic time before channel access is granted. The signaling used for channel access request is assumed to be as minimal as possible to ensure that delay experienced by the highest priority node is minimal. Fig. 3.1 shows the complete process with respect to the gateway. The mediation process repeats after each node has transmitted its data in order to handle the new users.

In our proposal, we consider that multiple nodes can access the channel simultaneously given that they have the same priority. To this end, we avail their transmissions. If a node belongs to N_i, it can immediately start its signaling to the gateway. However, if a node belongs to N_g, then it must sense its pre-assigned frequency for its availability. Although all the nodes of equal priority will use the same frequency for data transmission, only one node can utilize the frequency at a time to send the channel access request. Therefore, the frequency is allocated to the node on first come first serve basis. The rest of the nodes will wait until the frequency becomes available: that is, the channel energy condition is $C_i \leq C_{th}$ satisfied by continuously sensing the channel where C_{th} denotes the channel energy threshold. It is also pertinent to mention here that the requests are small enough that all the nodes belonging to N_g are able to communicate their requests to the gateway. This whole process is highlighted in Fig. 3.2 in a dotted red box, and labeled as multi-node signaling block. The gateway successfully receives the channel access requests from the nodes of both groups if the amplitude of the request signal X_n surpasses the minimum threshold X_{th} that is pre-defined at the gateway.

After the sequence in which nodes will access the channel is decided, node(s) having the highest priority will immediately access the channel and complete the transmission while the remaining nodes wait for their turn. Let WC denote the waiting cycles that a particular node has to wait before accessing the wireless medium. We define $\Lambda(F)'$ as a subset of $\Lambda(F)$ which includes frequencies assigned to the nodes that are in waiting. The $\Lambda(F)'$ is decremented by one after each mediation cycle. This implies that at the end of each cycle, all nodes associated with frequency f_i will be served and hence, f_i will be removed from subset $\Lambda(F)'$. The complete flow of the MEP-MAC

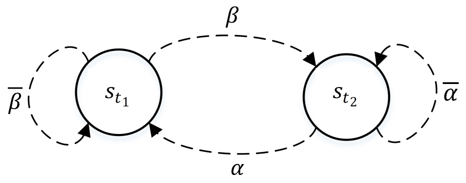

Figure 3.3: Markov decision process (MDP)

protocol is shown in Fig. 3.2.

Note that until $WC > 0$, the node(s) stay in OFF state. When $WC = 0$, the node(s) will go into active state and if there are no nodes with higher priority in the system, then channel will be made available. Otherwise, the nodes revert back to OFF state.

3.2 Mathematical Formulation

We use a two-state Markov decision process (MDP) of the form $\{s_{t_1}, s_{t_2}\}$ to model the system. The state s_{t_1} represents the inactive state and a node is in this state when the wireless medium is busy, i.e., the channel is allocated for data transmission to a higher priority node or a group of nodes. In case of a group of nodes, the priority of each node in the group will be the same and they will communicate with the gateway at the same frequency using NOMA. The state s_{t_2} represents the active state of a node. The state is reached when $WC = 0$ and the medium is available for data transmission. The nodes are also in state s_{t_2} while sending out requests for channel access to the gateway.

Fig. 3.3 shows the symbolic depiction of the two-state Markov decision process. The probability to switch from s_{t_1} to s_{t_2} is denoted by β. The probability to stay in state s_{t_1} is denoted by $\overline{\beta}$. The nodes will stay in state s_{t_1} if there are multiple waiting cycles involved or if higher priority nodes have reserved multiple data transmission slots for data transmission. However, in this paper, we assume that all nodes have the same packet size and it can be transmitted in a single slot.

The probability to switch from s_{t_2} to s_{t_1} is denoted by α. A node will go in state s_{t_1} after completing the data transmission. The nodes with lower priorities will move to state s_{t_1} while the channel is occupied by higher priority node(s). On the other hand, $\overline{\alpha}$ is the probability to stay in state s_{t_2}. The node(s) with the highest priority will stay in state s_{t_2} after the gateway has completed the channel access mediation, and will start data transmission.

We assume a fixed amount of nodes N in the network. In case of multiple equi-priority nodes, there can be many combinations and therefore, it is not possible to model the system by a generic discrete time Markov chain (DTMC). In order to develop a tractable discrete-time Markov chain (DTMC) model, we consider a 5-node example scenario in which the second and third nodes have the same priority and will transmit their data at the same frequency simultaneously by using NOMA. For comparison, we also consider the case in which each node is handled separately i.e. NOMA is not used. Fig. 3.4 shows the DTMC for above-described example.

The DTMC is described by four different states of the nodes, namely active_n, inactive_n, $\text{waiting}_n^{(j)}$ and data_l, where n is the nth node and l is the time slots in the maximum packet transmission duration L and j is the waiting stage of a node. The jth waiting stage will fall into the set $[0, 1, .., n-1-k]$ where $n = [1, 2, .., N]$ and k is an integer that increments

$$\mathbb{P}\{mathrmactive_n|\text{inactive}_n\} = \beta \tag{3.1}$$

$$\mathbb{P}\{\text{inactive}_n|\text{active}_n\} = \alpha \tag{3.2}$$

$$\mathbb{P}\{\text{waiting}_n^{(j-1)}|\text{waiting}_n^{(j-2)}\} = \overline{\beta} \tag{3.3}$$

$$\mathbb{P}\{\text{data}_l|\text{active}_n\} = \mu \tag{3.4}$$

The states and probabilities in Fig. 3.4 shown in dotted red exist if NOMA is not considered. Furthermore, it can be seen that every node has an additional waiting stage compared to the previous node which reflects the fact that each node will be independently given channel access. However, when NOMA is involved, multiple nodes can have the same number of states which implies that these nodes have been assigned the same priority for channel access and will transmit simultaneously.

We define the p-step probability to transition from active_n state to $\text{waiting}_n^{(j)}$ state in p steps as w_{nj} which is defined as

$$\mathbb{P}\{\text{waiting}_n^{(j)}|\text{active}_n\} = w_{nj} \tag{3.5}$$

The probability transition matrices for 5-node example are defined below. The matrix to the left implies that NOMA is not considered at the physical layer. However, the matrix is modified to the one on the right when MEP-MAC is implemented. With reference to Fig. 3.4, nodes 2 and 3 are sharing the same priority and will simultaneously access the medium. Therefore, one mediation cycle will be reduced for nodes 4 and 5 as reflected by the matrix

Eq. 4.7 can be generalized to n-step transition probability as

$$w_{nj} = \mathbb{P}\{\text{active}_n\} \times \left\{ \sum_{a=1}^{\binom{n-1}{j}} \left(\prod_{f_k \epsilon r(a)} \mathbb{P}\{\text{inactive}_n\} \right) \right\}, \tag{3.7}$$

where $\mathbb{P}\{\text{active}_n\}$ and $\mathbb{P}\{\text{inactive}_n\}$ are the steady state probabilities of being in active and inactive states respectively. The steady state probability $\mathbb{P}\{\text{active}_n\}$ will be different with respect to nodes. The node(s) having the highest priority will have the channel access immediately after priority has been mediated by the gateway. Hence, there will be no waiting time for such node(s). On the other hand, the nodes that are placed in the queue will have to go through some waiting time before getting channel access. Moreover, nodes having same priority will have equal values for $\mathbb{P}\{\text{active}_n\}$ and $\mathbb{P}\{\text{inactive}_n\}$. These steady state probabilities can be mathematically described as [44]

$$\mathbb{P}\{\text{active}_n\} = \begin{cases} \dfrac{\alpha\beta}{\alpha\beta + (\alpha\beta L + \beta)\mu_1 + \alpha^2}, & i = 1 \\ \dfrac{\alpha\beta}{\alpha\beta + (\alpha\beta L + \beta)\mu_2 + \alpha^2}, & i = 2 \\ \dfrac{\alpha\beta}{\alpha\beta + (\alpha\beta L + \beta)\mu_i + \alpha^2 + \alpha\vartheta_i}, & 3 \leq i \leq F \end{cases} \tag{3.8}$$

$$\mathbb{P}\{\text{inactive}_n^j\} = \mathbb{P}\{\text{active}_n\} \left\{ 1 + \sum_{j=1}^{n-1-k} \left(1 + \left(\frac{1-\beta}{\beta} \right)^j \right) \right\} \tag{3.9}$$

The above equations are categorized using frequency f_i, $i \in \Lambda(F)$ for n^{th} node as there can be multiple nodes over a single frequency. Hence for all such nodes, $\mathbb{P}\{\text{active}_n\}$ would be the same. The F denotes the highest frequency available for the transmission, and ϑ_i is a stochastic variable that models the waiting process of the nodes in line for channel access

$$\vartheta_i = \sum_{j=2}^{n-1} w_{nj} \sum_{k=0}^{j-2} \left(\frac{1-\beta}{\beta}\right)^k, \tag{3.10}$$

while μ_i is the probability to go from state active$_n$ to state data$_l$. This implies that node(s) that were previously in the waiting state have the highest priority amongst all nodes and can now access the channel for transmitting data. It can be found as

$$\mu_i = \alpha - \sum_{j=1}^{n-1} w_{nj} \tag{3.11}$$

3.3 Performance Analysis and Results

The performance analysis of the proposed protocol is performed by evaluating the throughput and latency of the system. The parameters defined by IEEE 802.15.4 MAC-sub layer are used to validate the performance and the results have been compared with NOMA-less scenario. Table 3.1 shows the parameters that are utilized for analysis.

3.3.1 System Throughput

The system throughput is defined as the ratio of transmission of payload bits to the total number of bits transmitted in a transmission slot. According to [45], the system throughput (S) can be determined as

$$S = \frac{P_{tr} P_s R_{\text{avg}} E[T_{\text{payload}}]}{P_{tr} P_s E[T] + P_{tr} \overline{P_s} E[T_{\text{queue}}] + \overline{P_{tr}} E[T_{\text{n}}]}, \tag{3.12}$$

Table 3.1: System Parameters for MEP-MAC

Parameter	**Description**	**Value**
r	Data rate for single node	250 kbps
P	Packet payload size	960 bits
T_{p}	Payload transmission time	3.84 ms
T_{arb}	Mediation Phase	10 ms
T_{startup}	Startup time	352 μs
λ	Turn around time	192 μs
T_{Tx}	Time to transmit channel access request	352 μs
T_{Rx}	Time to receive gateway's decision	640 μs
T_{phy}	Physical layer header duration	192 μs
T_{mac}	MAC layer header duration	224 μs
T_{n}	Non transmission time	320 μs

where $E[T_{\mathrm{payload}}]$ is the mean time for packet payload transmission, $E[T]$ is the mean time for the transmission of whole packet, $E[T_{\mathrm{queue}}]$ is the mean waiting time for a node if $\Lambda(F)' \neq 0$, which implies that there are higher priority nodes in the queue. Also, $E[T_{\mathrm{n}}]$ is the mean non-transmission time. The probability P_{tr} determines how the medium can be randomly occupied by the nodes for transmission, P_s is the probability that the transmission on the channel is successful and R_{avg} is the average transmission data rate. As the packet sizes are equal for all nodes, $R_{\mathrm{avg}} = r$ (see Table 3.1). The probabilities $\mathbb{P}_{tr}$ and $\mathbb{P}_s$ are given by [44]

$$P_{tr} = 1 - \prod_{i=1}^{N} (1 - \mu_i \mathbb{P}\{\text{active}_n\}) \tag{3.13}$$

$$P_s = \frac{\sum_{j=1}^{N} \tau_j \left(\prod_{i=j+1}^{N} (1 - \mu_i \mathbb{P}\{\text{active}_n\}) \right)}{\mathbb{P}_{tr}}, \tag{3.14}$$

where $\tau_n = \mu_n \mathbb{P}\{\text{active}_n\} = \mathbb{P}\{\text{data}_L\}$ for $1 \leq n \leq N$.

Fig. 4.4 shows the performance of the protocol in terms of system throughput with respect to β which is the probability that a particular node has some data to transmit. We utilize the 5-node example discussed before to observe the performance. It can be clearly seen that as the total number of transmission slots reduce, the system throughput improves. In the figure, the percentage slots depict the amount of slots utilized when NOMA is employed, as compared to the simple case where NOMA is not employed. Without NOMA, each user utilizes one timeslot to transmit data to the gateway. Whereas, NOMA allows multiple users to transmit simultaneously on a single timeslot, and thus the number of required timeslots is reduced. For instance for our 5 user case, the required timeslots with two equal priority users is 80% of total timeslots (i.e. 5 total timeslots). For the case of three equal priority users, the required time slots is 60% of total timeslots. Therefore, as can be observed from the figure, by employing NOMA the system throughput improves. Also, it can be observed that as β increases, the probability of transmission over the channel increases which in turn improves the system throughput.

Fig. 4.5 shows that as the number of nodes increase, the system throughput improves. Due to increased number of nodes requesting channel access, probability of channel occupancy will also increase. Furthermore, with the increased number of nodes, the probability of the channel to be successfully assigned to a node also increases. As a result, the system throughput improves. For instance at $N = 20$, MEP-MAC improves the system throughput approximately by 27% when 80% timeslots are used and by 68% when 60% of timeslots are used.

In Fig. 4.5, the results shown by solid lines are found by assuming NOMA

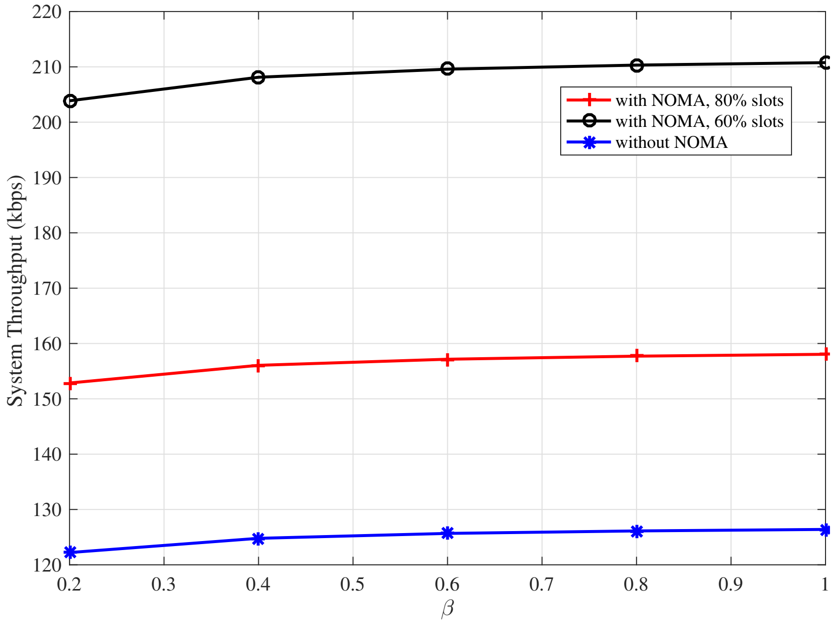

Figure 3.5: System throughput for the users $N = 5$

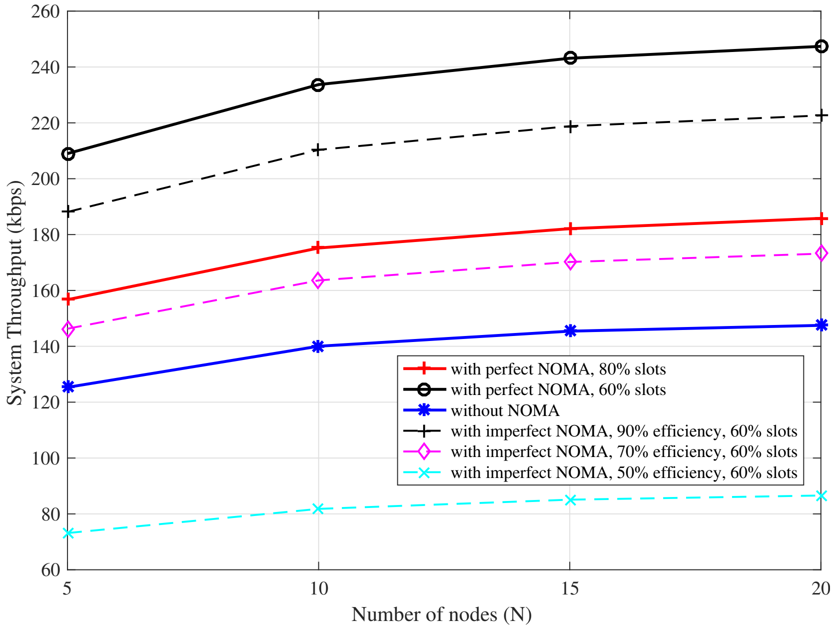

Figure 3.6: System throughput vs. number of nodes for $\beta = 0.5$. Dotted lines depict the effect of imperfect NOMA on performance.

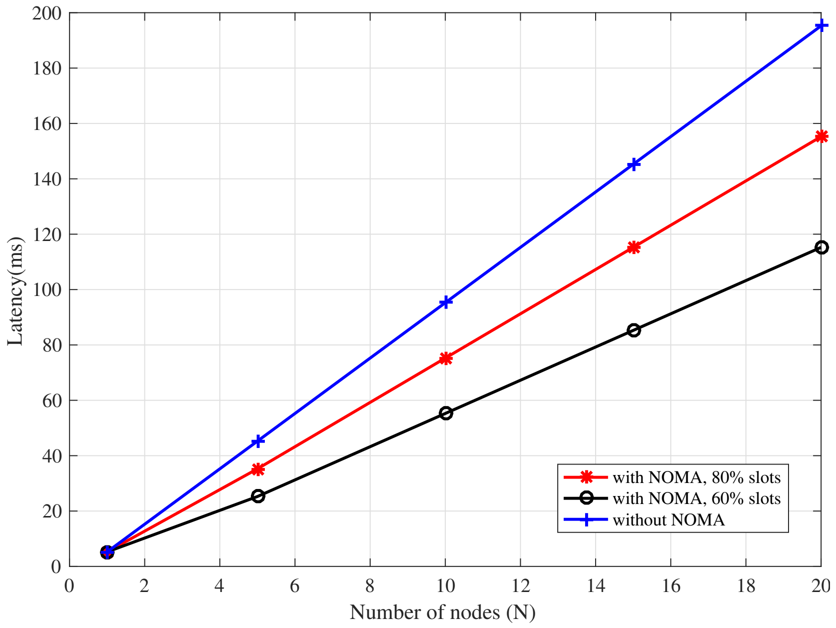

Figure 3.7: Latency vs. number of nodes

is perfectly executed. However, there can be many factors that will affect the execution of NOMA such as imperfections in decoding the data of users at the gateway and channel conditions. The degree to which there are imperfections in NOMA are depicted by the percentage efficiency. The lower the efficiency, higher will be the degree of imperfections in NOMA. The dotted curves show how the system throughput is impacted as the imperfection in NOMA increases. The graph also shows that there is a certain threshold above which the use of NOMA can be beneficial. However, if the threshold is not met, then the MEP-MAC fails and its better not to use NOMA at the physical layer.

3.3.2 Latency

Every node will experience some inevitable delay before getting channel access for data transmission as nodes transmit channel access requests to the gateway. The request phase consists of two main parts, i.e., 1) time for sending out the request to the gateway for channel access which is denoted by T_{Tx}; 2) time in reception of the decision taken by the gateway which is denoted by T_{Rx}. There is also a turn around time λ to switch between transmission and reception. For nodes that have to go through a waiting stage also experience some waiting time $T_{\mathrm{waiting}}(n)(n-1-k)T_{\mathrm{s}}$ which shows that the waiting time for a node is dependent upon the number of slots that it has to wait. With MEP-MAC, the number of waiting slots for any nth node will be less than the number of nodes having higher priority. The factor k caters for this as it increments for each node by $(m-1)$, where m denotes the number of nodes having same priority and hence, will be served in same transmission slot.

For simplicity, we assume that all the data packets are of the same size i.e., $E[T_{\mathrm{payload}}] = T_{\mathrm{payload}}$. For the analysis, we require the corresponding values of $E[T]$ and $E[T_{\mathrm{queue}}]$ which are

$$E[T] = T_{\mathrm{startup}}+\lambda+T_{\mathrm{Tx}}+\lambda+T_{\mathrm{Rx}}+\lambda+E[T_{\mathrm{data}}], \tag{3.15}$$

$$E[T_{\mathrm{queue}}] = T_{\mathrm{queue}} = T_{\mathrm{arb}}, \tag{3.16}$$

where T_{queue} is the time during which the channel is occupied. $E[T_{\mathrm{data}}]$ can be segregated using the equation

$$E[T_{\text{data}}] = T_{\text{phy}} + T_{\text{mac}} + E[T_{\text{payload}}], \tag{3.17}$$

Fig. 3.7 shows the impact of reduced transmission slots. It can be clearly observed that the latency reduces as the number of transmission slots reduce. For $N = 20$, MEP-MAC reduces the overall latency by 20% when 80% of timeslots are used and by 41% when 60% of timeslots are used. It is important to note here that overall system latency stays the same for any combination of nodes. However, latency experienced by individual node may vary depending on how the higher priority nodes are sequenced.

Chapter 4

Wireless Mediation for Multi-Hop Networks

Abundant literature is available on scheduling schemes for industrial applications. Authors of [46] provide a TDMA based scheduling mechanism for multi-hop wireless network while ensuring minimal delay. The algorithm first finds the transmission order of the network using integer programming while ensuring minimal delay in scheduling. Then, use conflict graphs with the transmission order to ensure that the scheduling is conflict-free. The work in [47] uses TDMA and slotted aloha in tandem for optimal scheduling in single-hop wireless network. Each timeslot is booked for a dedicated user or a group of users. The group of users on the same timeslot operate using slotted Aloha. This heuristic algorithm tries to maximize the probability of packets received at the destination by optimizing timeslot allocation to users or a group of users and compares it with the optimal schedule evaluated.

The work in [48] studied scheduling problem in TDMA-based wireless sensing and control networks. The physical network nodes are organized as logical hypernodes, which form a hypergraph. The scheduling is divided in dedicated and shared slot scheduling, where the former decides the number of timeslots for packet transmission to the destination, while the latter allows packets to share their allocated timeslots to further improve end-to-end reliability.

As evident from the literature cited above, most scheduling schemes are TDMA based. In case of time-critical industrial applications, in an event of emergency, the respective critical packets will have to wait for allotted timeslots to transmit the information rather than being serviced on priority. This is unacceptable for applications with stringent time constraints. By reserving an emergency slot to cater for above-mentioned situations, the channel utilization will be reduced, as the slot will go unutilized when there is no emergency data [49]. Although many real-time MAC protocols have been designed to cater for this problem. However, such protocols only reduce the data processing time between transmitter and receiver rather then reacting to the emergency situations.

WirArb [44] is a MAC protocol, specially designed to cater for harsh industrial environments, while ensuring deterministic channel access for nodes. By using WirArb in industries, a central gateway can control data reception from nodes by assigning priorities to network nodes. Hence, each node will have to wait for a deterministic time before getting channel access. The protocol gives improved results in terms of overall system throughput, worst-case latency and bandwidth efficiency, when compared with conventional techniques such as TDMA.

The above protocols however, does not consider nodes that are not in vicinity of the gateway but are part of the network. Such nodes can only reach the gateway by leveraging multi-hop communication. They must transmit their data via another node, termed as relay node, which must be within a reachable distance from the gateway. The relay node then forwards the data to the gateway. Hence, in this chapter, we research on multi-hop communication while not using TDMA as our basis for scheduling. We develop a theoretical stochastic model for multi-hop communication to analyze the performance in terms of system throughput and worst-case latency.

4.1 System Model

We assume a star topology with central control such that all nodes connect to a gateway residing at the center. The gateway decides the order by which it will receive data from the nodes. Nodes can be industrial devices such as sensors and actuators that send data to the gateway containing important information or statistics about the network. Because of time-critical nature of the industry, this communication has to be deterministic rather than stochastic. Hence, the gateway is responsible to ensure that every node communicates with in a specified time slot. To achieve this, the gateway receives channel access request from every node before the actual transmission. The data received by the gateway contains an identifier that indicates the level of priority with which a particular node wants channel access for data transmission. Each node that has sent a request for channel access to the gateway will indicate the urgency of its data through an identifier. The gateway uses this information to assign priorities to each node for channel access. This phase of communication is termed as the *decision phase.* Immediately after the end of the decision phase, the node having the highest priority will start accessing the channel and transmitting its data to the gateway while the remaining nodes will wait for some pre-determined time before getting their channel access. This phase of communication is termed as *data transmission phase.* The signaling done during the decision phase is as minimal as possible to make sure that the highest priority node can get channel access as quickly as possible.

The process however, is not as straight forward as described above. In this work, we also assume that not all nodes are within reachable distance from the gateway. Some nodes cannot directly transmit their data to the gateway due to larger distances. Such nodes must transmit data in a multi-hop manner by sending their data to the nearest node, which must also be within the vicinity of the gateway. That node will then relay information to the gateway.

For simplicity, we assume that nodes are distributed in tiers, as shown in Fig. 4.1. Tier 1 nodes can directly communicate with the gateway as they are within a reachable distance whereas tier 2 nodes are at distances larger than the threshold distance for direct communication. Such node will transmit their data via two-hop communication. A tier 2 node sends out its channel access request to the gateway. However, it will not receive any acknowledgement from the gateway, as the request was not delivered. Hence, after waiting for some known time, the node will broadcast a short burst requesting for a collaboration with a tier 1 node. It will partner with a tier

1 node whose response was received in the shortest time. It is pertinent to mention here that this procedure will take place only when network discovery occurs for the first time. For the subsequent decision and data transmission phases, this information will remain the same.

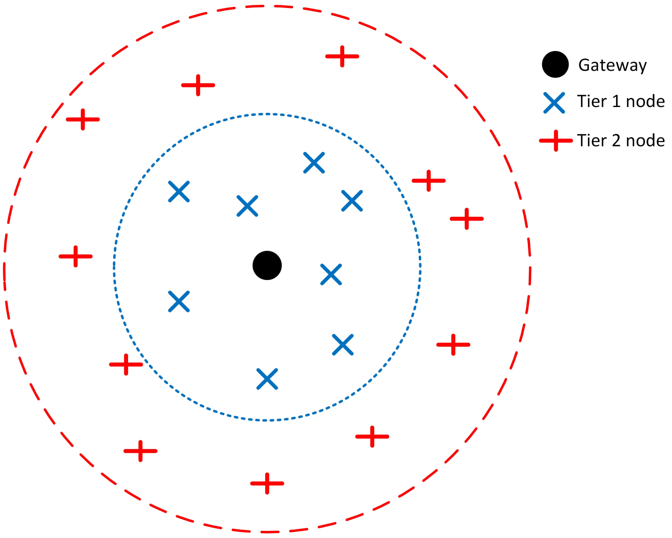

Figure 4.1: Users distribution in tiers

Fig. 4.2 shows a flowchart, which explains the complete process from the start of decision phase until the end of data transmission phase. The power of the request signal X_n of n^{th} node must be greater than the threshold power X_{th}, so that it can be detected by the gateway. After receiving channel access requests from all the nodes, gateway performs decision-making and assigns priorities to each user. This information is disseminated to all the nodes, which then either immediately access the channel or wait for their turn. WC denotes the waiting cycles that a particular node has to wait according to its assigned priority. We define Λ' as a subset of Λ which includes frequencies assigned to the users in waiting. The Λ' is decremented by one after a node

4.2 Mathematical Formulation

There are two main states in which a node can be during the process, active state and inactive state. Hence, we use a two state MDP to mathematically formulate our system model. A node is in *active* state when it is communicating with the gateway for data transmission, i.e., when its $WC = 0$. A node can also be in this state while sending out channel access request to the gateway. A node will go to active state from inactive state with a probability β. A node is in *inactive* state while waiting for its turn to access the medium or after finishing transmitting data to the gateway or if it is not in contention for channel access. A node will go in inactive state with probability α. A node stays in *inactive* state if $WC > 1$, which implies that there are multiple nodes having higher priority or the preceding nodes have reserved multiple time slots each for data transmission to the gateway.

We assume fixed number of K nodes where there are N tier 1 and M tier 2 nodes such that $K = N + M$. As there can be a large number of scenarios for channel access of nodes, therefore, if it not possible to model the system by a generic discrete time Markov chain (DTMC). Hence, in this paper, we consider a 5-node example in which $N = 3$ and $M = 2$. The DTMC for the above-mentioned scenario is depicted in Fig. 4.3.

The DTMC is described by the following four different states as shown in the figure:

1. Inactive state denoted by *inactive*.
2. Active state denoted by $active_k^{(x)}$, where k denotes a user and $x \epsilon \{1, 2\}$, $x = 1$ for tier 1 node and $x = 2$ for tier 2 node.

immediately while the other nodes experience waiting cycle(s) as per priorities assigned to them. As per the figure, tier 2 nodes go from *active* state to *relay* state to send data to a tier 1 node which then forwards it to the gateway. Eventually, each tier 2 node takes two transmission slots to send its data to the gateway. Hence, DTMC can be transformed into the one shown in Fig. 4.4

As every tier 2 node will first forward its data to a tier 1 node, it implies that these tier 1 nodes will attempt to access the channel twice i.e. for its own transmission and for forwarding the data of a tier 2 node. Hence for simplicity, we can assume that there are $K = N + 2M$ nodes. By utilizing this assumption, we can simplify the DTMC as shown. The states and state transition probabilities for tier 2 nodes are shown in red in Fig. 4.4. It can be observed that there are two successive nodes having their states and state transition probabilities in red. The first one shows that the tier 2 node has sent data to its collaborative tier 1 node while the second one shows that the tier 1 node has forwarded the information to the gateway.

The state transition probabilities between above-mentioned states can be described as

$$\mathbb{P}\{\text{active}_k|\text{inactive}_k\} = \beta \tag{4.1}$$

$$\mathbb{P}\{\text{inactive}_k|\text{active}_k\} = \alpha \tag{4.2}$$

$$\mathbb{P}\{\text{waiting}_{k(j-1)}|\text{waiting}_{k(j-2)}\} = \overline{\beta} \tag{4.3}$$

$$\mathbb{P}\{\text{data}|\text{active}_k\} = \mu \tag{4.4}$$

$$\begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ w_{21}^{(2)} & 0 & 0 & 0 & 0 & 0 \\ w_{31}^{(1)} & w_{32}^{(1)} & w_{33}^{(1)} & 0 & 0 & 0 \\ w_{41}^{(2)} & w_{42}^{(2)} & w_{43}^{(2)} & w_{44}^{(2)} & 0 & 0 \\ w_{51}^{(1)} & w_{52}^{(1)} & w_{53}^{(1)} & w_{54}^{(1)} & w_{55}^{(1)} & w_{56}^{(1)} \end{pmatrix}$$

This can be simplified into the matrix shown below, which can be found using Fig. 4.4. The matrix elements shown in red correspond to the states and state transition probabilities shown in red in Fig. 4.4.

$$\begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ w_{21}^{(2)} & 0 & 0 & 0 & 0 & 0 \\ w_{31}^{(2)} & w_{32}^{(2)} & 0 & 0 & 0 & 0 \\ w_{41}^{(1)} & w_{42}^{(1)} & w_{43}^{(1)} & 0 & 0 & 0 \\ w_{51}^{(2)} & w_{52}^{(2)} & w_{53}^{(2)} & w_{54}^{(2)} & 0 & 0 \\ w_{61}^{(2)} & w_{62}^{(2)} & w_{63}^{(2)} & w_{64}^{(2)} & w_{65}^{(2)} & 0 \\ w_{71}^{(1)} & w_{72}^{(1)} & w_{73}^{(1)} & w_{74}^{(1)} & w_{75}^{(1)} & w_{76}^{(1)} \end{pmatrix}$$

Each entry in the probability transition matrix can be found by evaluating a possible set of combination of nodes. One-step transition probability can be found as [44]

$$w_{k1} = \mathbb{P}\{\text{active}_k\} \times \sum_{i=1}^{k-1} \mathbb{P}\{\text{inactive}_k\} \tag{4.7}$$

Eq. 4.7 can be generalized to n-step transition probability as

$$w_{kj} = \mathbb{P}\{\text{active}_k\} \times \left\{ \sum_{a=1}^{\binom{k-1}{j}} \left(\prod_{f_i \epsilon r(a)} \mathbb{P}\{\text{inactive}_k\} \right) \right\}, \tag{4.8}$$

where $\mathbb{P}\{\text{active}_k\}$ and $\mathbb{P}\{\text{inactive}_k\}$ are the steady state probabilities of being in active and inactive states respectively. The steady state probability $\mathbb{P}\{\text{active}_k\}$ will be different with respect to nodes. The node having the highest priority will have the channel access immediately. Hence, there will be no waiting time for such a node. On the other hand, the nodes that are placed in the queue will have to experience delay in terms of waiting cycles before getting channel access. These steady state probabilities can be mathematically described as [44]

$$\mathbb{P}\{\text{active}_k\} = \begin{cases} \dfrac{\alpha\beta}{\alpha\beta + (\alpha\beta L + \beta)\mu_1 + \alpha^2}, & i = 1 \\ \dfrac{\alpha\beta}{\alpha\beta + (\alpha\beta L + \beta)\mu_2 + \alpha^2}, & i = 2 \\ \dfrac{\alpha\beta}{\alpha\beta + (\alpha\beta L + \beta)\mu_i + \alpha^2 + \alpha\vartheta_i}, & 3 \leq i \leq K \end{cases} \tag{4.9}$$

$$\mathbb{P}\{\text{inactive}_{kj}^{(x)}\} = \mathbb{P}\{\text{active}_k\} \left\{ 1 + \sum_{j=1}^{k-1} \left(1 + \left(\frac{1-\beta}{\beta} \right)^j \right) \right\} \tag{4.10}$$

ϑ_i is a stochastic variable which formulates the waiting process for nodes which are in queue for channel access

$$\vartheta_i = \sum_{j=2}^{n-1} w_{nj} \sum_{k=0}^{j-2} \left(\frac{1-\beta}{\beta} \right)^k, \tag{4.11}$$

Table 4.1: System Parameters for Multi-Hop

Parameter	**Description**	**Value**
r	Data rate for single node	250 kbps
P	Packet payload size	960 bits
T_p	Payload transmission time	3.84 ms
T_arb	Mediation Phase	10 ms
T_startup	Startup time	352 μs
λ	Turn around time	192 μs
T_Tx	Time to transmit channel access request	352 μs
T_Rx	Time to receive gateway's decision	640 μs
T_phy	Physical layer header duration	192 μs
T_mac	MAC layer header duration	224 μs
T_n	Non transmission time	320 μs
$T_\mathrm{propagation}$	Propagation delay	$3\mu s - 5\mu s$
$T_\mathrm{forwarding}$	Forwarding delay	$192\mu s$

while μ_i is the probability to go from state active$_n$ to state data$_l$. This implies that node(s) that were previously in the waiting state have the highest priority amongst all nodes and can now access the channel for transmitting data. It can be found as

$$\mu_i = \alpha - \sum_{j=1}^{n-1} w_{nj} \tag{4.12}$$

4.3 Performance Analysis and Results

The performance analysis of the proposed protocol is performed by evaluating the throughput and latency of the system. The parameters defined by IEEE 802.15.4 MAC-sub layer are used to validate the performance. Table 4.1 shows the parameters that are utilized for analysis.

4.3.1 System Throughput

The system throughput is defined as the ratio of transmission of payload bits to the total number of bits transmitted in a transmission slot. According to [45], the system throughput (S) can be determined as

$$S = \frac{P_{tr} P_s R_{\text{avg}} E[T_{\text{payload}}]}{P_{tr} P_s E[T] + P_{tr} \overline{P_s} E[T_{\text{queue}}] + \overline{P_{tr}} E[T_{\text{n}}]}, \tag{4.13}$$

where $E[T_{\text{payload}}]$ is the mean time for packet payload transmission, $E[T]$ is the mean time for the transmission of whole packet, $E[T_{\text{queue}}]$ is the mean waiting time for a node if $\Lambda(F)' \neq 0$, which implies that there are higher priority nodes in the queue. Also, $E[T_{\text{n}}]$ is the mean non-transmission time. The probability P_{tr} determines how the medium can be randomly occupied by the nodes for transmission, P_s is the probability that the transmission on the channel is successful and R_{avg} is the average transmission data rate. As the packet sizes are equal for all nodes, $R_{\text{avg}} = r$ (see Table 4.1). The probabilities P_{tr} and P_s are given by [44]

$$P_{tr} = 1 - \prod_{i=1}^{N} (1 - \mu_i \mathbb{P}\{\text{active}_n\}) \tag{4.14}$$

$$P_s = \frac{\sum_{j=1}^{N} \tau_j \left(\prod_{i=j+1}^{N} (1 - \mu_i \mathbb{P}\{\text{active}_n\}) \right)}{P_{tr}}, \tag{4.15}$$

where $\tau_n = \mu_n \mathbb{P}\{\text{active}_n\} = \mathbb{P}\{\text{data}_L\}$ for $1 \leq n \leq N$.

Fig. 4.5 shows the analytical and simulation results for multi-hop communication. The results in the figure are two-fold; the blue curve shows the effect on system throughput as Tier 2 nodes increase, while Tier 1 nodes are

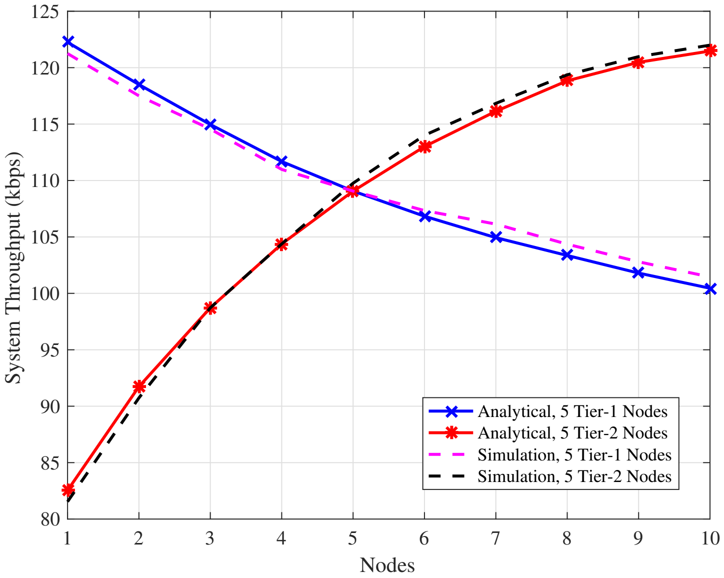

Figure 4.5: Users vs. System Throughput

constant. The results depict that as Tier 2 nodes increase, the overall system throughput starts to deteriorate. This is because each Tier 2 node takes two timeslots to transmit its data to the gateway, due to multi-hop communication. The contrasting results of the red curve depict that by keeping Tier 2 nodes constant and increasing Tier 1 nodes, the system throughput is improved. Because each tier 1 node takes only one timeslot to transmit its data to the gateway.

We also performed simulations and found the simulation results to match the analytical findings.

Fig. 4.6 is the contour plot for the system throughput against number of Tier-1 and Tier-2 users. From the graph, the system throughput of the network can be extracted for any combination of Tier-1 and Tier-2 nodes.

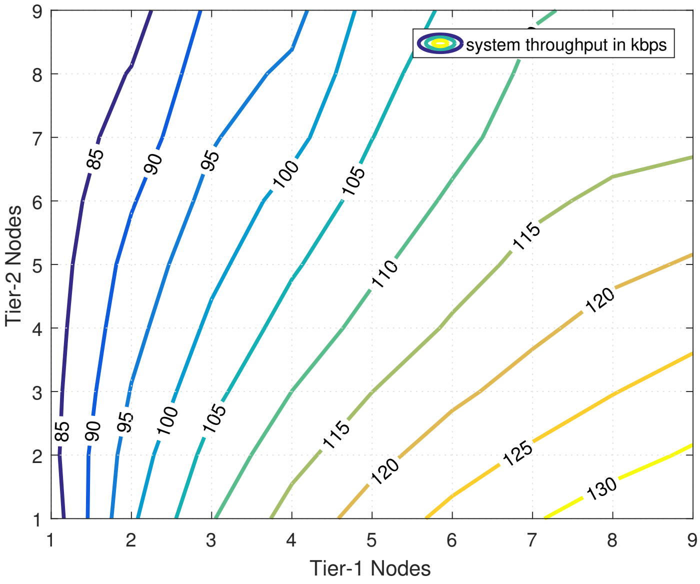

Figure 4.6: Contour plot of system throughput against different number of nodes in Tier-1 and Tier-2

4.3.2 Latency

Every node will experience some inevitable delay before getting channel access for data transmission as nodes transmit channel access requests to the gateway. The request phase consists of two main parts, i.e., 1) time for sending out the request to the gateway for channel access which is denoted by T_{Tx}; 2) time in reception of the decision taken by the gateway which is denoted by T_{Rx}. There is also a turn around time λ to switch between transmission and reception. For nodes that have to go through a waiting stage also experience some waiting time $T_{\mathrm{waiting}}(n) = (n-1)T_{\mathrm{s}}$ which shows that the waiting time for a node is dependent upon the number of slots that it has to wait. $T_{\mathrm{propagation}}$ is the propagation delay experienced by each node in the network while delivering its data to the gateway and is modeled by a

Fig. 4.7 shows the simulation results of delay experienced by a node. The results shows how delay can vary for each node depending on the priority it has been assigned by the gateway. The results show that the delay increases as the number of total node increase. The increase is linear. However, when tier 2 users are fixed and tier 1 users are increased, the average gradient is lower. This is because for each additional tier 1 node, one timeslot is added. However, for the case in which tier 2 nodes are increased, for each additional tier 2 node, two timeslots are added. Hence, the increment in latency is higher.

Fig. 4.8 shows the average worst-case latency experienced by a particular node. It can be observed that the worst-case latency with increase in the number of nodes in the network. The increase is higher when tier 2 users increase in the network, while tier 1 users are fixed as compared to the vice-versa case. The figure also shows the simulation results that almost match the analytical findings.

Fig. 4.6 is the contour plot for the average delay against number of Tier-1 and Tier-2 users. From the graph, the average worst-case can be extracted for any combination of Tier-1 and Tier-2 nodes.

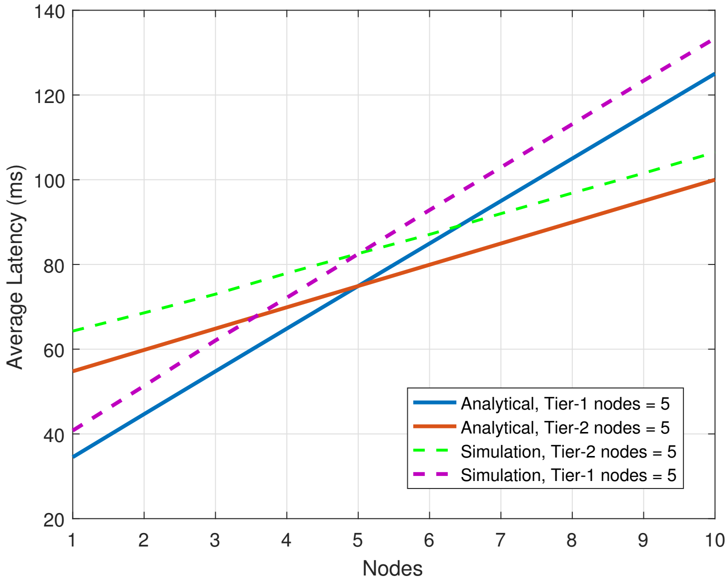

Figure 4.8: Average worst-case latency. Analytical and simulation results

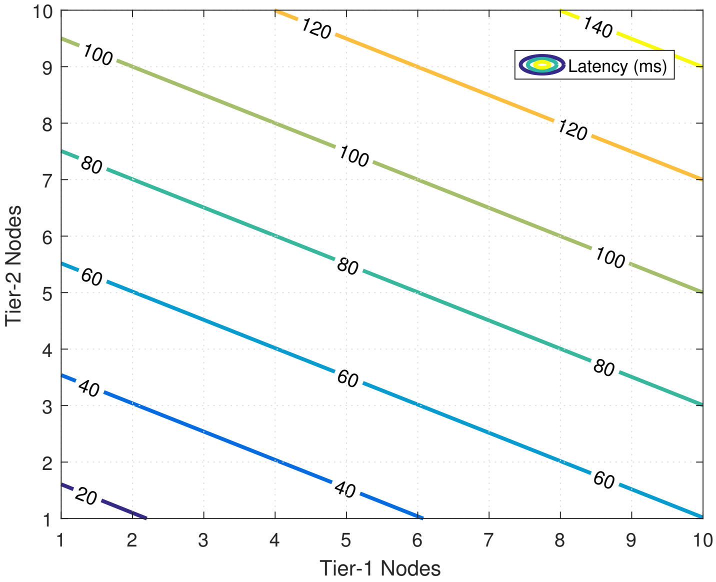

Figure 4.9: Contour plot of delay against different number of nodes in Tier-1 and Tier-2

Chapter 5

Conclusions and Future Directions

In this thesis, we first proposed a cross-layer protocol MEP-MAC that jointly exploits physical and MAC layer properties to allow multiple nodes having the same priority to access the wireless medium simultaneously. The MAC layer functionality of this protocol ensures that the most critical events are allowed channel access immediately while other events wait according to their urgency. At the physical layer, the protocol makes use of non-orthogonal multiple access (NOMA) technique to allow multiple nodes to access the channel in the same transmission slot. The results show that MEP-MAC gives improved results in the form of system throughput and latency. However, the performance is subject to the physical channel conditions.

We then extended our work to multi-hop network where nodes that are not in vicinity of the gateway forward their data to another node that relay information to the gateway. Through mathematical analysis and simulation, we showed that the system performance is better when Tier 1 nodes are higher in number than Tier 2 nodes.

5.1 Future Directions

As future works, we suggest the following:

1. To extend the proposed Multi-Hop protocol to support n-hop communication and optimization of performance parameters. Research will be required for downlink communication as well, as gateway will also be limited by distance.

2. Implement MEP-MAC on Multi-Hop scenario. The proposed MEP-MAC protocol will be evaluated to cater for various combinations of equal-priority nodes, including cross-tier nodes.

3. Evaluate the performance of proposed protocols with nodes having variable sized packets for transmission.

Bibliography

[1] L. Da Xu, W. He, and S. Li, “Internet of things in industries: A Survey,” *IEEE Transactions on industrial informatics*, vol. 10, no. 4, pp. 2233–2243, 2014.

[2] A. Whitmore, A. Agarwal, and L. Da Xu, “The Internet of Things A survey of topics and trends,” *Information Systems Frontiers*, vol. 17, no. 2, pp. 261–274, 2015.

[3] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, “Internet of things: A survey on enabling technologies, protocols, and applications,” *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 2347–2376, 2015.

[4] P. Sethi and S. R. Sarangi, “Internet of things: Architectures, Protocols, and Applications,” *Journal of Electrical and Computer Engineering*, vol. 2017, 2017.

[5] Z. Dong, Z. Yian, L. Wangbao, G. Jianhua, and W. Yunlan, “Object service provision in Internet of Things,” in *e-Education, e-Business, e-Management, and e-Learning, 2010. IC4E’10. International Conference on*, pp. 234–237, IEEE, 2010.

[6] P. C. Garrido, G. M. Miraz, I. L. Ruiz, and M. Á. Gómez-Nieto, "A model for the development of NFC context-awareness applications on Internet of Things," in *Near Field Communication (NFC), 2010 Second International Workshop on*, pp. 9–14, IEEE, 2010.

[7] A. J. J. Valera, M. A. Zamora, and A. F. Skarmeta, "An architecture based on internet of things to support mobility and security in medical environments," in *Consumer Communications and Networking Conference (CCNC), 2010 7th IEEE*, pp. 1–5, IEEE, 2010.

[8] A. Dohr, R. Modre-Opsrian, M. Drobics, D. Hayn, and G. Schreier, "The internet of things for ambient assisted living," in *Information Technology: New Generations (ITNG), 2010 Seventh International Conference on*, pp. 804–809, IEEE, 2010.

[9] A. J. Jara, F. J. Belchi, A. F. Alcolea, J. Santa, M. A. Zamora-Izquierdo, and A. F. Gómez-Skarmeta, "A Pharmaceutical Intelligent Information System to detect allergies and Adverse Drugs Reactions based on Internet of Things," in *Pervasive Computing and Communications Workshops (PERCOM Workshops), 2010 8th IEEE International Conference on*, pp. 809–812, IEEE, 2010.

[10] S. Bandyopadhyay, M. Sengupta, S. Maiti, and S. Dutta, "Role of middleware for internet of things: a study," *International Journal of Computer Science and Engineering Survey*, vol. 2, no. 3, pp. 94–105, 2011.

[11] G. Broll, E. Rukzio, M. Paolucci, M. Wagner, A. Schmidt, and H. Hussmann, "Perci: Pervasive service interaction with the internet of things," *IEEE Internet Computing*, vol. 13, no. 6, pp. 74–81, 2009.

[12] M. Darianian and M. P. Michael, "Smart home mobile RFID-based internet-of-things systems and services," in *Advanced Computer Theory and Engineering, 2008. ICACTE'08. International Conference on*, pp. 116–120, IEEE, 2008.

[13] J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," *Computer networks*, vol. 52, no. 12, pp. 2292–2330, 2008.

[14] O. P. Günther, W. Kletti, and U. Kubach, *RFID in Manufacturing*. Springer Science & Business Media, 2008.

[15] G. Wu, S. Talwar, K. Johnsson, N. Himayat, and K. D. Johnson, "M2M: From mobile to embedded internet," *IEEE Communications Magazine*, vol. 49, no. 4, 2011.

[16] Y. Zhang, R. Yu, S. Xie, W. Yao, Y. Xiao, and M. Guizani, "Home m2m networks: architectures, standards, and qos improvement," *IEEE Communications Magazine*, vol. 49, no. 4, 2011.

[17] Y. Li, M. Hou, H. Liu, and Y. Liu, "Towards a theoretical framework of strategic decision, supporting capability and information sharing under the context of internet of things," *Information Technology and Management*, vol. 13, no. 4, pp. 205–216, 2012.

[18] L. Atzori, A. Iera, and G. Morabito, “The internet of things: A survey,” *Computer networks*, vol. 54, no. 15, pp. 2787–2805, 2010.

[19] D. Miorandi, S. Sicari, F. De Pellegrini, and I. Chlamtac, “Internet of things: Vision, applications and research challenges,” *Ad hoc networks*, vol. 10, no. 7, pp. 1497–1516, 2012.

[20] H. Sundmaeker, P. Guillemin, P. Friess, and S. Woelfflé, “Vision and challenges for realising the internet of things,” *Cluster of European Research Projects on the Internet of Things, European Commision*, vol. 3, no. 3, pp. 34–36, 2010.

[21] H. Zhang and L. Zhu, “Internet of things: Key technology, architecture and challenging problems,” in *Computer Science and Automation Engineering (CSAE), 2011 IEEE International Conference on*, vol. 4, pp. 507–512, IEEE, 2011.

[22] M. C. Domingo, “An overview of the internet of things for people with disabilities,” *Journal of Network and Computer Applications*, vol. 35, no. 2, pp. 584–596, 2012.

[23] Z. Pang, Q. Chen, J. Tian, L. Zheng, and E. Dubrova, “Ecosystem analysis in the design of open platform-based in-home healthcare terminals towards the internet-of-things,” in *Advanced Communication Technology (ICACT), 2013 15th International Conference on*, pp. 529–534, IEEE, 2013.

[24] H. Alemdar and C. Ersoy, “Wireless sensor networks for healthcare: A survey,” *Computer networks*, vol. 54, no. 15, pp. 2688–2710, 2010.

[25] I. Plaza, L. MartíN, S. Martin, and C. Medrano, "Mobile applications in an aging society: Status and trends," *Journal of Systems and Software*, vol. 84, no. 11, pp. 1977–1988, 2011.

[26] Z. Pang, Q. Chen, W. Han, and L. Zheng, "Value-centric design of the internet-of-things solution for food supply chain: Value creation, sensor portfolio and information fusion," *Information Systems Frontiers*, vol. 17, no. 2, pp. 289–319, 2015.

[27] B. Karakostas, "A DNS architecture for the internet of things: A case study in transport logistics," *Procedia Computer Science*, vol. 19, pp. 594–601, 2013.

[28] E. Qin, Y. Long, C. Zhang, and L. Huang, "Cloud computing and the internet of things: Technology innovation in automobile service," in *International Conference on Human Interface and the Management of Information*, pp. 173–180, Springer, 2013.

[29] Y. Zhang, B. Chen, and X. Lu, "Intelligent monitoring system on refrigerator trucks based on the internet of things," in *International Conference on Wireless Communications and Applications*, pp. 201–206, Springer, 2011.

[30] C. G. Keller, T. Dang, H. Fritz, A. Joos, C. Rabe, and D. M. Gavrila, "Active pedestrian safety by automatic braking and evasive steering," *IEEE Transactions on Intelligent Transportation Systems*, vol. 12, no. 4, pp. 1292–1304, 2011.

[31] Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, and K. Higuchi, "Non-orthogonal multiple access (NOMA) for cellular future radio access," in *77th IEEE Vehicular Technology Conference (VTC Spring)*, pp. 1-5, June 2013.

[32] Z. Ding, Z. Yang, P. Fan, and H. V. Poor, "On the performance of non-orthogonal multiple access in 5G systems with randomly deployed users," *IEEE Signal Process. Lett.*, vol. 21, pp. 1501–1505, Dec 2014.

[33] Z. Ding, P. Fan, and H. V. Poor, "User pairing in non-orthogonal multiple access downlink transmissions," in *IEEE Global Communications Conference (GLOBECOM)*, pp. 1-5, Dec 2015.

[34] Z. Ding, M. Peng, and H. V. Poor, "Cooperative non-orthogonal multiple access in 5G systems," *IEEE Commun. Lett.*, vol. 19, pp. 1462–1465, Aug 2015.

[35] Y. Liu, Z. Ding, M. Elkashlan, and H. V. Poor, "Cooperative non-orthogonal multiple access with simultaneous wireless information and power transfer," *IEEE J. Sel. Areas Commun.*, vol. 34, pp. 938–953, April 2016.

[36] Q. Shafi and S. A. Hassan, "Interference analysis in cooperative multi-hop networks subject to multiple flows," in *IEEE Wireless Days (WD)*, pp. 1-6, Nov 2014.

[37] A. Ijaz, S. A. Hassan, S. A. R. Zaidi, D. N. K. Jayakody, and S. M. H. Zaidi, "Coverage and rate analysis for downlink hetnets using modified

reverse frequency allocation scheme," *IEEE Access*, vol. 5, pp. 2489–2502, 2017.

[38] X. Li, "Space-time coded multi-transmission among distributed transmitters without perfect synchronization," *IEEE Signal Process. Lett.*, vol. 11, pp. 948–951, Dec 2004.

[39] S. Qureshi, S. A. Hassan, and D. N. K. Jayakody, "Divide-and-allocate: An uplink successive bandwidth division noma system," *Trans. Emerging Tel. Tech*, 2016.

[40] H. Munir, S. A. Hassan, H. Pervaiz, Q. Ni, and L. Musavian, "Energy efficient resource allocation in 5G hybrid heterogeneous networks: A game theoretic approach," in *IEEE Vehicular Technology Conference (VTC)*, pp. 1–5, 2016.

[41] S. A. R. Naqvi and S. A. Hassan, "Combining NOMA and mmWave technology for cellular communication," in *IEEE Vehicular Technology Conference (VTC-Fall)*, pp. 1–5, 2016.

[42] S. Qureshi, S. A. Hassan, and D. N. K. Jayakody, "Successive bandwidth division NOMA systems: Uplink power allocation with proportional fairness," in *IEEE Annual Consumer Communications & Networking Conference (CCNC)*, pp. 998–1003, 2017.

[43] Z. Ding, Y. Liu, J. Choi, Q. Sun, M. Elkashlan, I. Chih-Lin, and H. V. Poor, "Application of non-orthogonal multiple access in LTE and 5G networks," *IEEE Communications Magazine*, vol. 55, no. 2, pp. 185–191, 2017.

[44] T. Zheng, M. Gidlund, and J. Åkerberg, "WirArb: A new MAC protocol for time critical industrial wireless sensor network applications," *IEEE Sensors Journal*, vol. 16, no. 7, pp. 2127–2139, 2016.

[45] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535–547, 2000.

[46] P. Djukic and S. Valaee, "Delay aware link scheduling for multi-hop tdma wireless networks," *IEEE/ACM Transactions on Networking (TON)*, vol. 17, no. 3, pp. 870–883, 2009.

[47] H. Zhang, M. Albert, and A. Willig, "Combining TDMA with slotted Aloha for delay constrained traffic over lossy links," in *Control Automation Robotics & Vision (ICARCV), 2012 12th International Conference on*, pp. 701–706, IEEE, 2012.

[48] M. Yan, K.-Y. Lam, S. Han, E. Chan, Q. Chen, P. Fan, D. Chen, and M. Nixon, "Hypergraph-based data link layer scheduling for reliable packet delivery in wireless sensing and control networks with end-to-end delay constraints," *Information Sciences*, vol. 278, pp. 34–55, 2014.

[49] M. Khanafer, M. Guennoun, and H. T. Mouftah, "A survey of beacon-enabled IEEE 802.15.4 MAC protocols in wireless sensor networks," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 2, pp. 856–876, 2014.