Wireless Mediation of Multiple Equi-Priority Events in Time-Critical Industrial Applications

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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 (PHY) and MAC layers is needed. In this paper, we propose a protocol termed as multiple equi-priority MAC (MEP-MAC) which combines the functions of MAC and PHY layers: the MAC layer ensures a deterministic behavior of the system by assigning priorities to the nodes, while non-orthogonal multiple access (NOMA) at PHY 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 up to 70% and 40% improvement in terms of system throughput and latency respectively as compared to a system that does not leverage NOMA at PHY layer.

CCS CONCEPTS

• **Networks** → *Network protocol design*;

KEYWORDS

Time-critical events, cross-layer design, NOMA

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1 INTRODUCTION

The concept of smart city envisions use of information technology to make services provided to residents, workers and visitors more efficient, interactive and reliable. A similar concept of smart industries has emerged which allows automation of industrial processes. Industrial automation has gained a lot of attention recently because of increasing demand for higher efficiency, productivity, and profits. Wired communication technologies were introduced for industrial automation quite earlier which although fulfilled the demands for improved efficiency and productivity, the challenging settings, expensive deployment, and maintenance costs hindered the implementation of wired automation systems in many industrial scenarios [3]. In this respect, wireless technologies have much to offer in this domain. For instance, information from many of the industrial devices such as critical rotating equipment can be extracted relatively easily by using wireless technologies [1]. As a result, wireless technologies are becoming increasingly popular for the industrial automation domain [2], as they also offer rapid deployment and maintenance, cost-effectiveness, scalability, and self-organization.

However, due to harsh wireless channel conditions in industrial environments there are many challenges that need to be addressed to meet the quality of service requirements of industrial applications [6]. The traditional protocols such as carrier sense multiple access-collision avoidance (CSMA/CA) cannot be used in time-critical industrial setup due to stringent delay requirements. Much research has been done on the protocols that might be suitable for harsh industrial conditions and also cater for deterministic delay requirements. Some of the current standards available today include WirelessHART [9], ISA 100.11a [7] and WIA-PA [10]. These standards combine time division multiple access (TDMA) and CSMA/CA channel access techniques to schedule channel access for the nodes with deterministic delays. However in case of emergency, the node has to wait for its time slot, which is unacceptable.

Emergency enabled MAC (EE-MAC)[8] addresses this problem by adding special emergency slots between two regular time slots. The protocol adaptively allows emergency data to be transmitted in the current slot which ensures that the delay requirements are met. WirArb [11] is another MAC protocol designed specifically for delay-stringent industrial applications. The protocol allows a central gateway to provide channel access to the nodes on priority

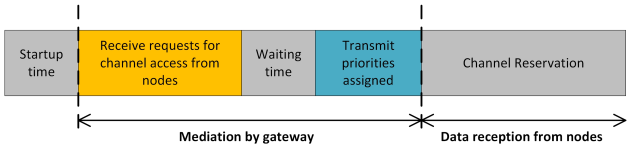

Figure 1: Mediation process as seen from the gateway

basis by assigning them arbitration frequencies where the node having the lowest frequency will be assigned the highest priority and vice-versa.

To the best of our knowledge, none of the existing protocols handle the simultaneous channel access of equal priority nodes. In this paper, we propose a protocol termed as multiple equi-priority MAC (MEP-MAC) which combines the functions of physical (PHY) 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 PHY layer, it leverages the non-orthogonal multiple access (NOMA) technique [5], 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 under non-ideal physical conditions.

The rest of the paper is organized as follows. Section 2 describes the system model and the proposed protocol. Section 3 presents the mathematical formulation. In Section 4, we analyze the performance of the protocol and conclude the paper in Section 5.

2 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. 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 NOMA at PHY layer to allow these nodes to communicate with the gateway concurrently. The NOMA technique allows the gateway to service multiple nodes at same time, frequency and code but different power levels. The gateway allocates

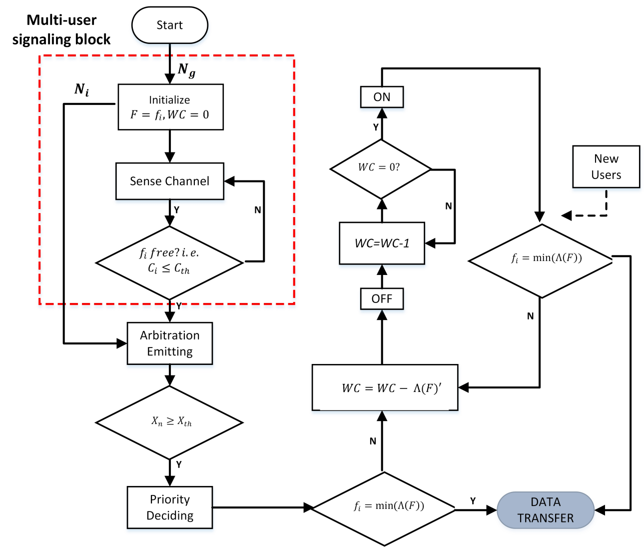

Figure 2: Flowchart for MEP-MAC. The multi-node signaling block is shown in dotted red box.

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.

The signaling frequencies are assigned from a set denoted by $\Lambda(F)$. As we consider multiple equi-priority nodes, such nodes are pre-allocated same frequency for transmission to the gateway. Therefore, $|\Lambda(F)| \leq N$, where $|\Lambda(F)|$ denotes the cardinality of set $\Lambda(F)$ and N is the total number of the network nodes. The nodes can be divided into two categories: individual nodes, denoted by N_i, and grouped nodes, denoted by N_g, such that $N_g \cup N_i = N$. The N_i consists of the nodes that are not sharing their assigned frequencies with any other node, whereas N_g contains the nodes having same priorities and use the same frequencies to communicate with the gateway.

At the start of the mediation process, channel access request window opens in which the nodes can send requests to the gateway for scheduling 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

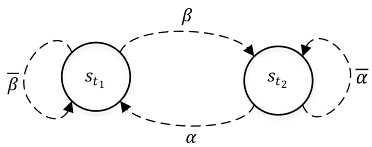

Figure 3: Markov decision process (MDP)

are able to communicate their requests to the gateway. This whole process is highlighted in Fig. 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 protocol is shown in Fig. 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 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 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 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. 4 shows the DTMC for above-described example.

The DTMC is described by four different states of the nodes, namely active$_n$, inactive$_n$, 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 by $(m-1)$ whenever the channel is accessible to the nodes having the same priority. The total number of nodes in a single transmission slot are denoted by m. To cater for the waiting cycles for the waiting nodes, a factor k is added that decreases when multiple nodes are transmitting simultaneously. For instance, consider three nodes in the network requesting for channel access but node 1 and node 2 are having the same priority. Then, node 3 will have to wait for just one transmission slot before channel access is granted. The state transition probabilities between above mentioned states can be described as

$$P\{\text{active}_n|\text{inactive}_n\} = \beta \tag{1}$$

$$P\{\text{inactive}_n|\text{active}_n\} = \alpha \tag{2}$$

$$P\{\text{waiting}_n^{(j-1)}|\text{waiting}_n^{(j-2)}\} = \overline{\beta} \tag{3}$$

$$P\{\text{data}_l|\text{active}_n\} = \mu \tag{4}$$

The dotted states and probabilities in Fig. 4 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 implies that each node will be independently given channel access. However, when NOMA is involved, multiple nodes can have the same number of states that implies similar prior assignment and simultaneous channel access.

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

$$P\{\text{waiting}_n^{(j)}|\text{active}_n\} = w_{nj} \tag{5}$$

The probability transition matrices for 5-node example are defined below. The matrix to the left implies that NOMA is not considered at the PHY layer. However, the matrix is modified to the one on the right when MEP-MAC is implemented. With reference to Fig. 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 bold matrix elements.

$$\begin{pmatrix} 0 & 0 & 0 & 0 \\ w_{21} & 0 & 0 & 0 \\ w_{31} & w_{32} & 0 & 0 \\ w_{41} & w_{42} & w_{43} & 0 \\ w_{51} & w_{52} & w_{53} & w_{54} \end{pmatrix} \Rightarrow \begin{pmatrix} 0 & 0 & 0 & 0 \\ w_{21} & 0 & 0 & 0 \\ w_{31} & \mathbf{0} & 0 & 0 \\ w_{41} & w_{42} & \mathbf{0} & 0 \\ w_{51} & w_{52} & w_{53} & \mathbf{0} \end{pmatrix}$$

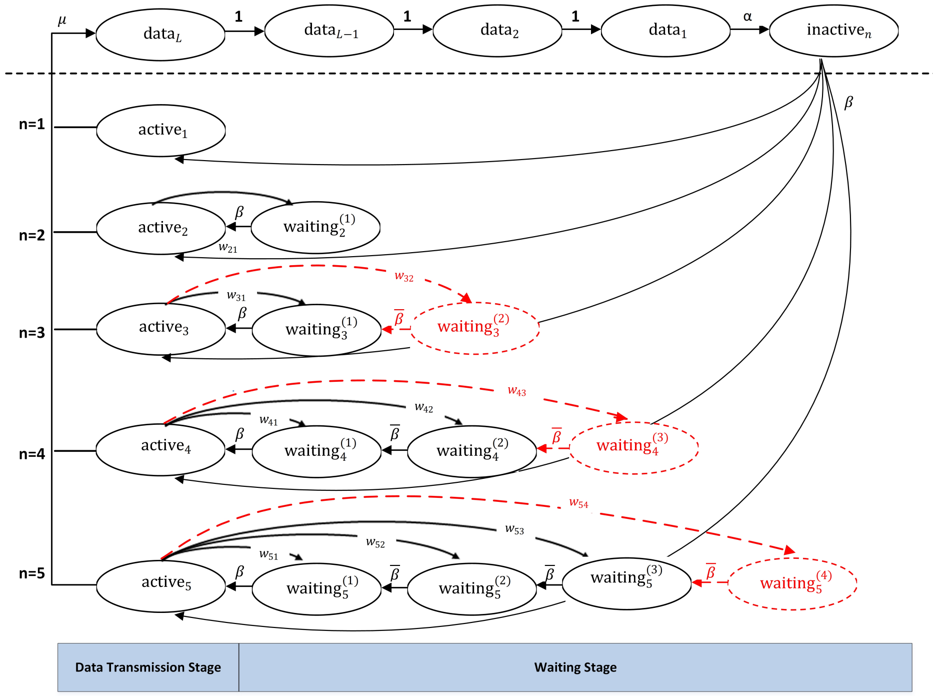

Figure 4: Discrete time Markov chain model. The dotted states and probabilities do not exist when NOMA is considered at PHY layer

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 [11]

$$w_{n1} = P\{\text{active}_n\} \times \sum_{k=1}^{n-1} P\{\text{inactive}_n\} \tag{6}$$

which finds all the combinations of nodes with higher priority than node n. As this is 1-step transition probability and the nodes of same priority are grouped together to transmit in same slot with frequency f_i, it implies that the node(s) will be next in line for transmission. Moreover, due to the grouping, there can be multiple nodes accessing the channel simultaneously. However, the waiting will be decided based on the number of frequencies assigned to higher priority nodes rather than the number of those nodes. With reference to Fig. 4, the fourth node i.e. $n = 4$ will have to wait for two transmission slots because nodes 2 and 3 have the same priority. Hence, reducing delay experienced by the node and improving throughput.

Eq. 6 can be generalized to n-step transition probability as

$$w_{nj} = P\{\text{active}_n\} \times \left\{ \sum_{a=1}^{\binom{n-1}{j}} \left(\prod_{f_k \epsilon r(a)} P\{\text{inactive}_n\} \right) \right\}, \tag{7}$$

where $P\{\text{active}_n\}$ and $P\{\text{inactive}_n\}$ are the steady state probabilities of being in active and inactive states respectively. The steady state probability $P\{\text{active}_n\}$ 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. 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 $P\{\text{active}_n\}$ and $P\{\text{inactive}_n\}$. These steady state probabilities can be mathematically described as [11]

$$P\{\text{active}_n\} = \begin{cases} \dfrac{\alpha\beta}{\alpha\beta + (\alpha\beta L + \beta)\mu_1 + \alpha^2}, & i = 1 \\ \dfrac{\alpha\beta}{\alpha\beta + (\alpha\beta L + \beta)\mu_2 + \alpha^2}, & i = 2 \\ \dfrac{\alpha\beta}{\alpha\beta + (\alpha\beta L + \beta)\mu_i + \alpha^2 + \alpha\vartheta_i}, & 3 \le i \le F \end{cases} \tag{8}$$

$$P\{\text{inactive}_n^j\} = P\{\text{active}_n\} \left\{ 1 + \sum_{j=1}^{n-1-k} \left(1 + \left(\frac{1-\beta}{\beta} \right)^j \right) \right\} \tag{9}$$

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, $P\{\text{active}_n\}$ 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

$$\vartheta_i = \sum_{j=2}^{n-1} w_{nj} \sum_{k=0}^{j-2} \left(\frac{1-\beta}{\beta} \right)^k, \tag{10}$$

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

Table 1: System Parameters

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

the channel for transmitting data. It can be found as

$$\mu_i = \alpha - \sum_{j=1}^{n-1} w_{nj} \tag{11}$$

4 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 1 shows the parameters that are utilized for analysis.

4.1 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 [4], the system throughput (S) can be determined as

$$S = \frac{P_{tr} P_s R_{\text{avg}} E[T_{\text{payload}}]}{P_{tr} P_s E[T] + P_{tr} \overline{P_s} E[T_{\text{queue}}] + \overline{P_{tr}} E[T_{\text{n}}]}, \tag{12}$$

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 1). The probabilities P_{tr} and P_s are given by [11]

$$P_{tr} = 1 - \prod_{i=1}^{N} (1 - \mu_i P\{\text{active}_n\}) \tag{13}$$

$$P_s = \frac{\sum_{j=1}^{N} \tau_j \left(\prod_{i=j+1}^{N} (1 - \mu_i P\{\text{active}_n\}) \right)}{P_{tr}}, \tag{14}$$

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

Fig. 5 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

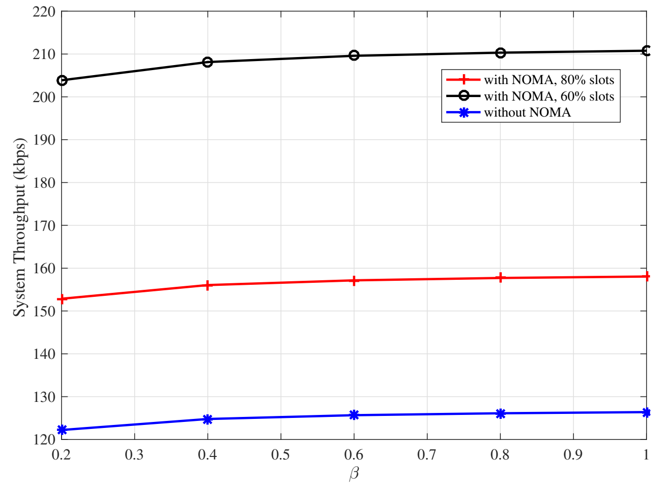

Figure 5: System throughput for the users $N = 5$

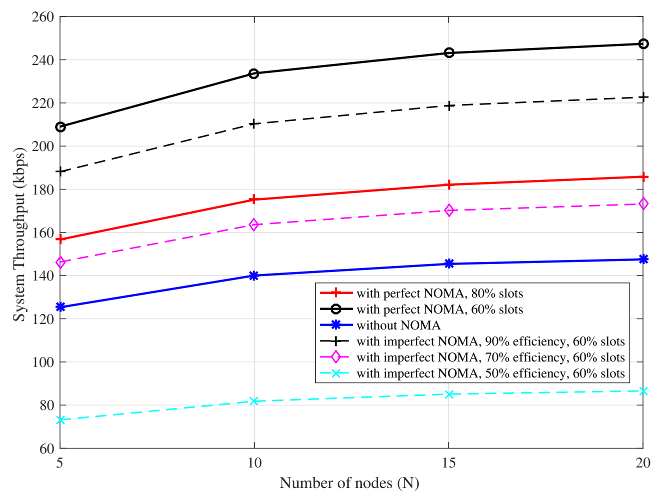

Figure 6: System throughput vs. number of nodes for $\beta = 0.5$. Dotted lines depict the effect of imperfect NOMA on performance.

example discussed before to observe the performance. The system throughput improves as number of transmission slots reduce. 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 reducing timeslots. 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, the throughput improves by employing NOMA. 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. 6 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. 6, the results shown by solid lines are found by assuming NOMA 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 PHY layer.

4.2 Latency

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 $T_{\text{waiting}}(n)(n-1-k)T_s$ 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., $E[T_{\text{payload}}] = T_{\text{payload}}$. For the analysis, we require the corresponding values of $E[T]$ and $E[T_{\text{queue}}]$ which are

$$E[T] = T_{\text{startup}} + \lambda + T_{\text{Tx}} + \lambda + T_{\text{Rx}} + \lambda + E[T_{\text{data}}], \tag{15}$$

$$E[T_{\text{queue}}] = T_{\text{queue}} = T_{\text{arb}}, \tag{16}$$

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

$$E[T_{\text{data}}] = T_{\text{phy}} + T_{\text{mac}} + E[T_{\text{payload}}], \tag{17}$$

Fig. 7 shows the impact of reduced transmission slots. 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. The overall system latency stays the same for any combination of nodes. However, latency experienced by each node may vary depending on how the higher priority nodes are sequenced.

5 CONCLUSION

In this paper, we proposed a cross-layer protocol MEP-MAC that jointly exploits PHY 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

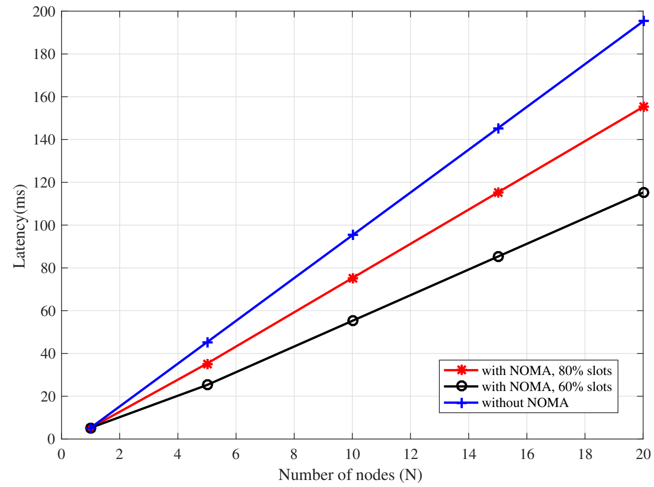

Figure 7: Latency vs. number of nodes

that the most critical events are allowed channel access immediately while other events wait according to their urgency. At PHY layer, the protocol makes use of 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.

REFERENCES

[1] Johan Åkerberg, Mikael Gidlund, and Mats Björkman. 2011. Future research challenges in wireless sensor and actuator networks targeting industrial automation. In *9th IEEE International Conference on Industrial Informatics (INDIN), 2011*. IEEE, 410–415.

[2] Ian F Akyildiz, Tommaso Melodia, and Kaushik R Chowdhury. 2007. A survey on wireless multimedia sensor networks. *Computer networks* 51, 4 (2007), 921–960.

[3] Bonnie Bennett, Mark Boddy, Frank Doyle, Mo Jamshidi, and Tunde Ogunnaike. 2004. *Assessment Study on Sensors and Automation in the Industries of the Future. Reports on Industrial Controls, Information Processing, Automation, and Robotics*. Technical Report. Office of Energy Efficiency and Renewable Energy (EERE), Washington, DC (United States).

[4] Giuseppe Bianchi. 2000. Performance analysis of the IEEE 802.11 distributed coordination function. *IEEE J. Sel. Areas Commun.* 18, 3 (2000), 535–547.

[5] Zhiguo Ding, Yuanwei Liu, Jinho Choi, Qi Sun, Maged Elkashlan, I Chih-Lin, and H Vincent Poor. 2017. Application of non-orthogonal multiple access in LTE and 5G networks. *IEEE Commun. Mag.* 55, 2 (2017), 185–191.

[6] Vehbi C Gungor and Gerhard P Hancke. 2009. Industrial wireless sensor networks: Challenges, design principles, and technical approaches. *IEEE Trans. Ind. Electron.* 56, 10 (2009), 4258–4265.

[7] ISA ISA100. 2009. 100.11 a-2009: Wireless systems for industrial automation: Process control and related applications. *International Society of Automation: Research Triangle Park, NC, USA* (2009).

[8] Mohsin Raza, Hoa Le-Minh, Nauman Aslam, Sajjad Hussain, and Waqas Ellahi. 2017. A control channel based MAC protocol for time critical and emergency communications in Industrial Wireless Sensor Networks. In *Int. Conf. Commmunication, Computing and Digital Systems (C-CODE)*. IEEE, 122–126.

[9] Jianping Song, Song Han, Al Mok, Deji Chen, Mike Lucas, Mark Nixon, and Wally Pratt. 2008. WirelessHART: Applying wireless technology in real-time industrial process control. In *and Embedded Technology and Applications Symposium. RTAS'08*. IEEE, 377–386.

[10] Min Wei and Keecheon Kim. 2012. Intrusion detection scheme using traffic prediction for wireless industrial networks. *Journal of Communications and Networks* 14, 3 (2012), 310–318.

[11] Tao Zheng, Mikael Gidlund, and Johan Åkerberg. 2016. WirArb: A new MAC protocol for time critical industrial wireless sensor network applications. *IEEE Sensors J.* 16, 7 (2016), 2127–2139.