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Wireless Mediation for Multi-Hop Networks in Time Critical Industrial Applications

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***Abstract*—Industrial Internet-of-things (IIoT) networks have recently gained enormous attention because of the huge advantages they offer. A typical IIoT network consists of a large number of sensor and actuator devices distributed randomly in an industrial area to automate various processes, where a major goal is to collect data from all these devices and to process it centrally at an aggregator. However, for an efficient system operation, a proficient scheduling mechanism is required due to its direct association with performance parameters. Many existing techniques such as time division multiple access (TDMA), do not perform well in industrial environments due to their stringent timeliness requirements. In this paper, we propose a medium access control (MAC) layer protocol for node scheduling in a scenario where some devices may not be in one-hop range of the aggregator and thus renders a multi-hop mechanism inevitable. A discrete time Markov chain (DTMC) model is proposed to characterize the transmission of multi-tier nodes and the analytical expressions of throughput and latency are derived. It has been oberved that the delay scales linearly with the number of nodes which are away not in one-hop distance of the aggregator. Numerical simulations have been performed to validate the theoretical results.**

***Index Terms*—Wireless mediation, multi-hop communication, internet of things, time-critical events**

I. INTRODUCTION

Wireless technologies are all set to take over wired technologies in industrial automation domain due to various advantages such as easier deployment and maintenance, flexibility, scalability and low cost [1]. The industrial environment, however, has time-stringent and deterministic channel access requirements. Various standards such as WirelessHART [2], ISA 100.11a [3] and WIA-PA [4] are already adopted which can satisfy the requirements of industrial automation applications. However, the scheduling of sporadic and time critical events in these standards is an open problem, which has a direct impact on the throughput and latency of the system.

The optimal scheduling for time-critical industrial applications is investigated extensively in the literature. For instance, in [5], the authors developed a TDMA-based scheduling mechanism for multi-hop wireless network while ensuring minimal delay. The algorithm, at first, finds the transmission order of the network using integer programming while ensuring minimal delay in scheduling. Later, it uses conflict graphs with the transmission order to guarantee that the scheduling is conflict-free.

In [6], TDMA and slotted ALOHA are utilized in tandem for optimal scheduling in single-hop wireless network. Each timeslot is reserved for a dedicated user or a group of users. The group of users on the same timeslot operates using slotted ALOHA. This 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.

In [7], the physical 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 improve end-to-end reliability.

It is worth noting that most of the scheduling schemes are based on the allocation of dedicated slots to the nodes. However, in case of an emergency event in time-critical applications, the emergency reporting nodes will have to wait for allocated timeslots rather than being granted channel access depending on the priority of the event. This is unacceptable for handling emergencies, which can otherwise cause safety and equipment failures. Moreover, reserving emergency slots to report emergencies reduces channel utilization, as the slot are unutilized in the absence of an emergency event [8]. Although many real-time MAC protocols have been designed to address this issue [9], [10], these protocols only reduce the data processing time between transmitter and receiver instead of reacting to emergency situations.

WirArb [11] is a MAC protocol that is specially designed to provide deterministic channel access for the nodes reporting emergency events. In WirArb, a central aggregator or gateway controls data reception from nodes by assigning them the priorities. Therein, each node waits for a deterministic time before gaining channel access. The protocol significantly enhances the system throughput, worst-case latency and bandwidth efficiency when compared with traditional TDMA techniques. MEP-MAC [12] is another protocol for time-critical industrial applications which utilizes Non-Orthogonal Multiple Access (NOMA) at physical layer to allow multiple equi-priority nodes to access the channel simultaneously, given that all nodes are within the vicinity of the central gateway.

None of the above-mentioned protocols cater for nodes which are not within one-hop range from the gateway. Hence, in this paper, we study the scenario of multi-hop communication utilized by such nodes. These nodes first pair with a relay node, which is essentially a node that can reach the gate-

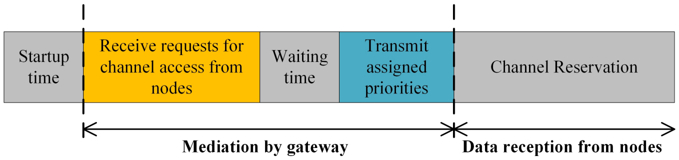

Fig. 1. Mediation process as seen from the gateway

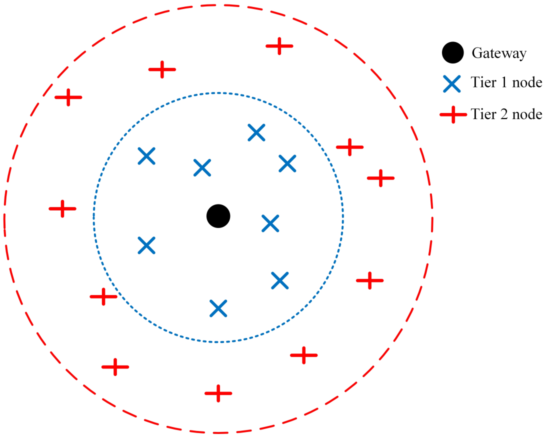

Fig. 2. Users distribution in tiers

way via single-hop communication. The far-end nodes then transmit data to their respective relay nodes, which relay data towards the gateway. We develop a analytical stochastic model for multi-hop communication to analyze the performance in terms of system throughput and worst-case latency.

The rest of the paper is organized as follows. Section II describes the system model for multi-hop communication. In section III, we present the mathematical formulation for performance analysis and, we present the results in Section IV. We conclude our work in Section V.

II. SYSTEM MODEL

We first explain the complete mediation process. We assume 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 data, this communication has to be deterministic rather than stochastic. Hence, the gateway is responsible to ensure that every node communicates within 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 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. Fig. 1 shows the complete mediation process as seen from the gateway.

The process however, is not as straight forward as described above. In this work, we also take into account nodes which are unable to communicate with the gateway due to large distance from the gateway and limited transmission power. Such nodes send their data to the nearest node, located within the vicinity of the gateway. That node then relays information to the gateway.

For simplicity, we assume that the nodes are distributed in two tiers, as shown in Fig. 2. 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 nodes 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 is received in the shortest time. Note that this procedure will take place only during network initialization phase. For the subsequent decision and data transmission phases, this information will remain the same.

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. W_c denotes the waiting cycles that a particular node has to wait according to its assigned priority. For an nth node, $W_c = (\mathrm{n}-1)$.

The waiting nodes are placed in OFF (inactive) state for energy conservation. As the waiting time is deterministic, node will automatically switch to ON state (active) state when $W_c = 0$ is applicable. However, if during OFF state, any new nodes with higher priority are introduced in the system, the node will again go back into OFF state as their waiting time is revised.

III. MATHEMATICAL FORMULATION

A node can be in one of the two states, i.e., active state and inactive state, which we represent by a Markov Decision Process (MDP) to model our system mathematically. A node is in *active* state when it is communicating with the gateway for data transmission, i.e., when its $W_c = 0$. 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 completing transmitting data to the gateway or if it is not in contention

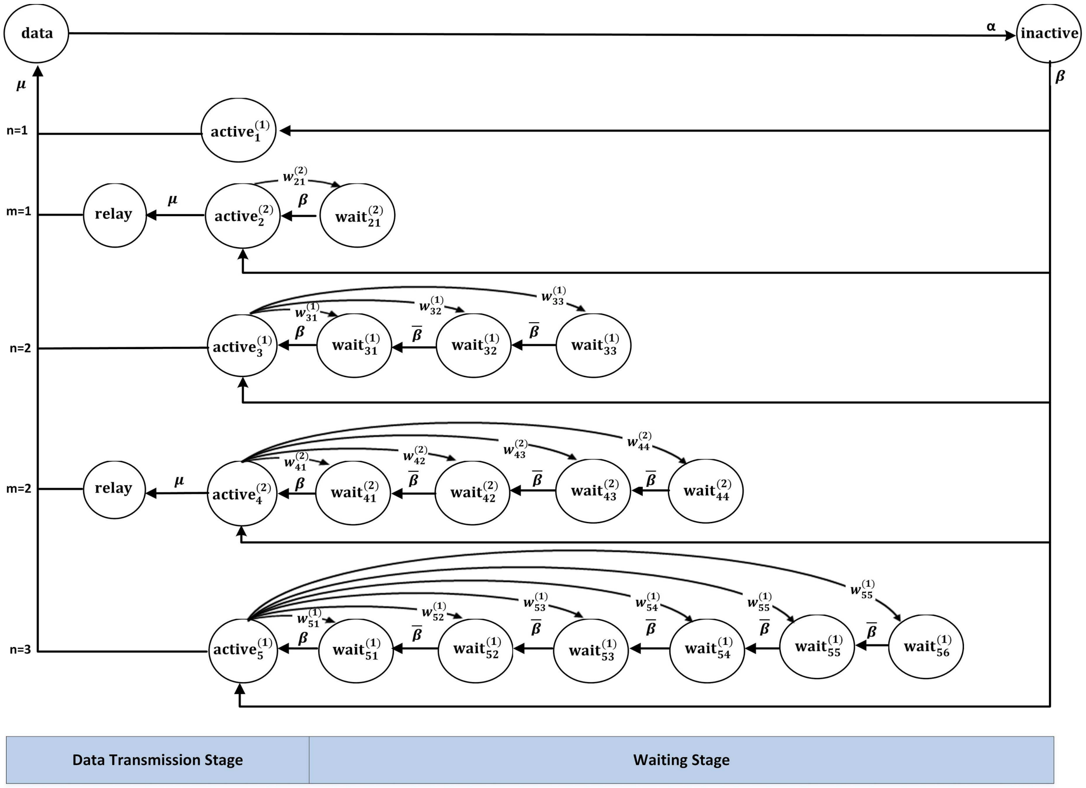

Fig. 3. Discrete time Markov chain model

for channel access. A node will move to inactive state with probability α. A node stays in $inactive$ state if $W_c > 1$, 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 nodes, K, where there are N Tier-1 and M Tier-2 nodes such that $K = N + M$. As an example, we consider a 5-node example in which $N = 3$ and $M = 2$. The DTMC for the above-mentioned scenario is depicted in Fig. 3.

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

1) Inactive state denoted by $inactive_k^{(x)}$, where k denotes a user and $x \epsilon \{1, 2\}$, $x = 1$ for Tier-1 node and $x = 2$ for Tier-2 node.
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.
3) Waiting state denoted by $wait_{kj}^{(x)}$, where k denotes the node, j denotes the waiting state a node is in. The jth waiting stage will fall into the set [0,1,..,K-1], where K is the total number of nodes in the system.
4) Relay state is denoted by $relay$. This state is experienced exclusively by Tier-2 nodes which move from $active$ state to $relay$ state to transmit the data to its partnered Tier-1 node. The node will then forward data to the gateway.
5) Data state is denoted by $data$. A node is in data state when it has completed its assigned waiting states (if any) and now has channel access for data transmission.

As seen from the DTMC in Fig. 3, the first node gets channel access 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.

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

$$\mathbb{P}\{\text{active}_k^{(x)} | \text{inactive}_k^{(x)}\} = \beta \tag{1}$$

$$\mathbb{P}\{\text{inactive}_k^{(x)} | \text{active}_k^{(x)}\} = \alpha \tag{2}$$

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

$$\mathbb{P}\{\text{data}_k^{(x)} | \text{active}_k^{(x)}\} = \mu \tag{4}$$

$$\mathbb{P}\{\text{relay} | \text{active}_k^{(x)}\} = \mu \tag{5}$$

The p-step probability from $\text{active}_k^{(x)}$ state to $\text{waiting}_{kj}^{(x)}$ in p transitions can be denoted by $w_{kj}^{(x)}$. This probability can be defined as follows

$$\mathbb{P}\{\text{waiting}_{kj}^{(x)} | \text{active}_k^{(x)}\} = w_{kj}^{(x)} \tag{6}$$

The probability transition matrices for 5-node example are defined below. The following matrix is formed while referencing Fig. 3.

TABLE I
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
$T_{\mathrm{propagation}}$	Propagation delay	$3\mu s - 5\mu s$

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

We can break the data transmission of Tier-2 node in two parts; (1) Tier-2 node sends data to a Tier-1 node and, (2) Tier-1 node forwards the data to the gateway. As these are separate transmission, we can simplify the above matrix as given below. There are pair of rows colored red in the matrix, where the first one denotes the first part of Tier-2 transmission and the second row denotes the second part of the transmission.

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

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 [11]

$$w_{k1}^{(x)} = \mathbb{P}\{\text{active}_k^{(x)}\} \times \sum_{i=1}^{k-1} \mathbb{P}\{\text{inactive}_k^{(x)}\} \tag{7}$$

Eq. (7) can be generalized to n-step transition probability as

$$w_{kj}^{(x)} = \mathbb{P}\{\text{active}_k^{(x)}\} \times \left\{ \sum_{a=1}^{\binom{k-1}{j}} \left(\prod_{f_i inr(a)} \mathbb{P}\{\text{inactive}_k^{(x)}\} \right) \right\}, \tag{8}$$

where $\mathbb{P}\{\text{active}_k^{(x)}\}$ and $\mathbb{P}\{\text{inactive}_k^{(x)}\}$ are the steady state probabilities of being in active and inactive states respectively. The steady state probability $\mathbb{P}\{\text{active}_k^{(x)}\}$ 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 [11]

$$\mathbb{P}\{\text{active}_k^{(x)}\} = \begin{cases} \dfrac{\alpha\beta}{\alpha\beta + (\alpha\beta L + \beta)\mu_1 + \alpha^2}, & i = 1 \\ \dfrac{\alpha\beta}{\alpha\beta + (\alpha\beta L + \beta)\mu_2 + \alpha^2}, & i = 2 \\ \dfrac{\alpha\beta}{\alpha\beta + (\alpha\beta L + \beta)\mu_i + \alpha^2 + \alpha\vartheta_i}, & 3 \leq i \leq K \end{cases} \tag{9}$$

$$\mathbb{P}\{\text{inactive}_k^{(x)}\} = \frac{1}{\beta}\left[\alpha - \sum_{j=2}^{k} \left(\frac{1-\beta}{\beta}\right)^{(j-2)} w_k^{(j-1)}\right] \times \mathbb{P}\{\text{active}_k^{(x)}\} \tag{10}$$

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

$$\vartheta_i = \sum_{j=2}^{k-1} w_{kj}^{(x)} \sum_{l=0}^{j-2} \left(\frac{1-\beta}{\beta}\right)^l, \tag{11}$$

while μ_i is the probability to go from state $\text{active}_n^{(x)}$ 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

$$\mu_i = \alpha - \sum_{j=1}^{k-1} w_{kj}^{(x)} \tag{12}$$

IV. 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 I shows the parameters that are utilized for analysis.

A. 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 [13], the system throughput (S) can be determined as

$$S = \frac{P_{tr} P_s R_{\mathrm{avg}} E[T_{\mathrm{payload}}]}{P_{tr} P_s E[T] + P_{tr} \overline{P_s} E[T_{\mathrm{queue}}] + \overline{P_{tr}} E[T_{\mathrm{n}}]}, \tag{13}$$

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

$$P_{tr} = 1 - \prod_{i=1}^{K} \left(1 - \mu_i \mathbb{P}\{\mathrm{active}_i^{(x)}\}\right) \tag{14}$$

$$P_s = \frac{\sum_{j=1}^{N} \tau_j \left(\prod_{i=j+1}^{K} \left(1 - \mu_i \mathbb{P}\{\mathrm{active}_i^{(x)}\}\right)\right)}{P_{tr}}, \tag{15}$$

where $\tau_k = \mu_k \mathbb{P}\{\mathrm{active}_k^{(x)}\} = \mathbb{P}\{\mathrm{data}_L\}$ for $1 \leq k \leq K$.

Fig. 4 shows the analytical and simulation results for system throughput, which are matching closely. The blue curve shows the effect on system throughput as the number of Tier-2 nodes increase while Tier-1 nodes are kept 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. This is because each Tier-1 node takes only one timeslot to transmit its data to the gateway.

Fig. 5 shows the contour plot of system throughput for Tier-1 and Tier-2 nodes, which can be utilized to find system throughput for any combination of Tier-1 and Tier-2 nodes.

B. 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 $T_{\mathrm{waiting}}(k) = (k-1)T_{\mathrm{s}}$ 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 which is assumed to be approximately 3 μs to 5 μs.

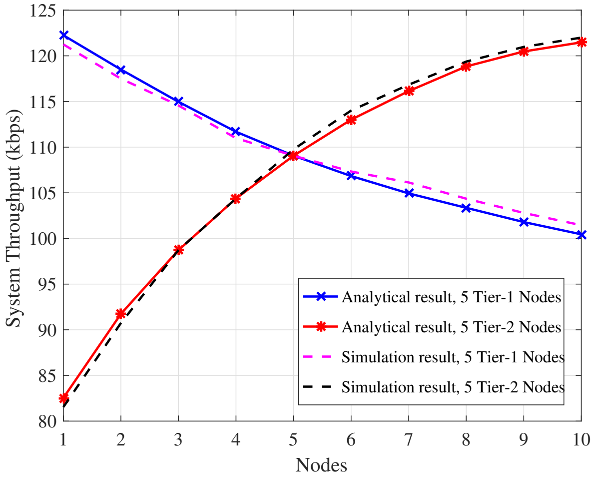

Fig. 4. System throughput with respect to the number of nodes in the network

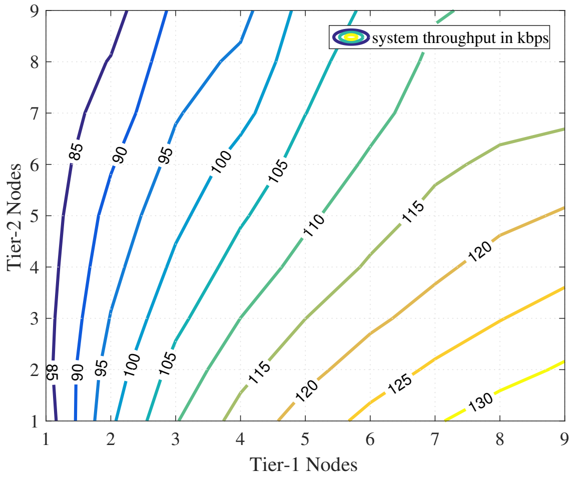

Fig. 5. Contour plot of system throughput with respect to the number of nodes in Tier-1 and Tier-2

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

$$E[T] = T_{\mathrm{startup}} + \lambda + T_{\mathrm{Tx}} + \lambda + T_{\mathrm{Rx}} + \lambda + E[T_{\mathrm{data}}], \tag{16}$$

$$E[T_{\mathrm{queue}}] = T_{\mathrm{queue}} = T_{\mathrm{arb}}, \tag{17}$$

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

$$E[T_{\mathrm{data}}] = T_{\mathrm{phy}} + T_{\mathrm{mac}} + E[T_{\mathrm{payload}}], \tag{18}$$

Fig. 6 shows the average worst-case latency experienced by a particular node. The results shows how delay can vary for each node depending on the priority it has been assigned

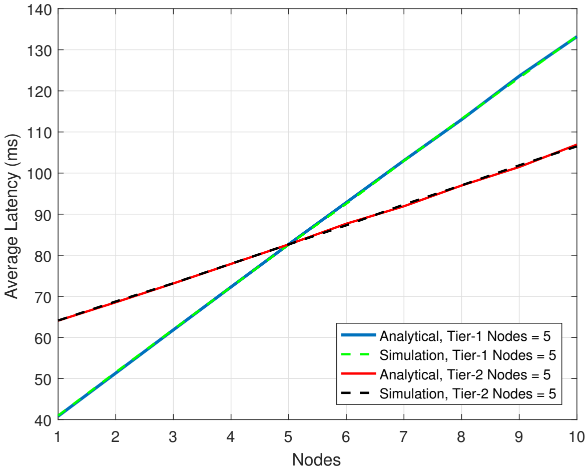

Fig. 6. Analytical and simulation results on average worst-case latency.

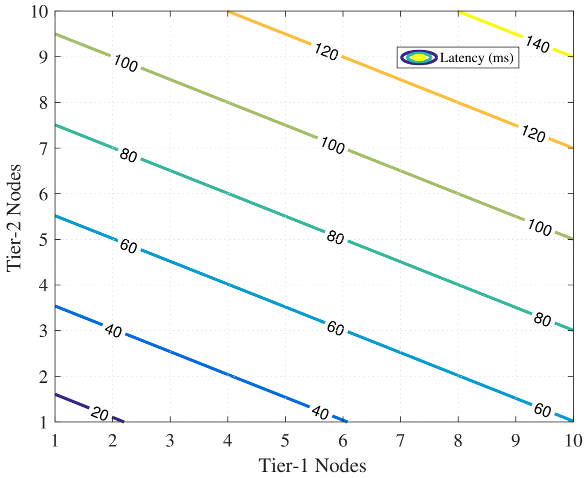

Fig. 7. Contour plot of delay under different number of nodes in Tier-1 and Tier-2

by the gateway. Generally, the results show that the delay increases linearly with the number of nodes. It can be depicted by the figure that when Tier-2 nodes are fixed and Tier-1 nodes are increased, the increment in average latency is lower as compared to the vice-versa case. Reason being that 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. The figure shows the simulation results to be matching with the analytical findings.

Fig. 7 shows the contour plot of latency for Tier-1 nodes represented on x-axis and Tier-2 nodes represented on y-axis. Using this result, we can extract the average delay experienced for any combination of nodes.

V. CONCLUSION

In this paper, we studied scheduling for multi-hop wireless network in time critical industrial applications. We presented a theoretical stochastic model to analyze the system performance in terms of system throughput and latency. The results showed that the overall performance of the system is better when Tier-1 nodes are higher in number than Tier-2 nodes. This is because each Tier-1 node occupies one timeslot, while each Tier-2 node takes two timeslots for transmission. We also conducted simulations and found the results to be matching with the analytical findings. This work can be extended for multiple equi-priority nodes in different tiers. The main challenge will be to cater for equi-priority nodes that are in different tiers and how such nodes can communicate with the gateway simultaneously.

REFERENCES

[1] V. C. Gungor and G. P. Hancke, “Industrial wireless sensor networks: Challenges, design principles, and technical approaches,” *IEEE Trans. Ind. Electron*, vol. 56, no. 10, pp. 4258–4265, 2009.

[2] J. Song, S. Han, A. Mok, D. Chen, M. Lucas, M. Nixon, and W. Pratt, “WirelessHART: Applying wireless technology in real-time industrial process control,” in *IEEE Real-Time and Embedded Technology and Applications Symposium*, 2008, pp. 377–386.

[3] I. ISA100, “100.11 a-2009: Wireless systems for industrial automation: Process control and related applications,” *International Society of Automation: Research Triangle Park, NC, USA*, 2009.

[4] M. Wei and K. Kim, “Intrusion detection scheme using traffic prediction for wireless industrial networks,” *J. of Commun. Netw*, vol. 14, no. 3, pp. 310–318, 2012.

[5] P. Djukic and S. Valaee, “Delay aware link scheduling for multi-hop tdma wireless networks,” *IEEE/ACM Trans. Netw.*, vol. 17, no. 3, pp. 870–883, 2009.

[6] H. Zhang, M. Albert, and A. Willig, “Combining TDMA with slotted Aloha for delay constrained traffic over lossy links,” in *IEEE Intl. Conf. on Control Automation Robotics & Vision (ICARCV)*, 2012, pp. 701–706.

[7] 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.

[8] M. Khanafer, M. Guennoun, and H. T. Mouftah, “A survey of beacon-enabled IEEE 802.15.4 MAC protocols in wireless sensor networks,” *IEEE Commun. Surveys Tuts.*, vol. 16, no. 2, pp. 856–876, 2014.

[9] A. Sgora, D. J. Vergados, and D. D. Vergados, “A survey of TDMA scheduling schemes in wireless multihop networks,” *ACM Computing Surveys (CSUR)*, vol. 47, no. 3, p. 53, 2015.

[10] M. Nobre, I. Silva, and L. A. Guedes, “Routing and scheduling algorithms for WirelessHARTNetworks: a survey,” *Sensors*, vol. 15, no. 5, pp. 9703–9740, 2015.

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

[12] S. F. Hassan, A. Mahmood, S. A. Hassan, and M. Gidlund, “Wireless mediation of multiple equi-priority events in time-critical industrial applications,” in *Proc. of the 1st ACM MobiHoc Workshop on Networking and Cybersecurity for Smart Cities*, ser. SmartCitiesSecurity’18. New York, NY, USA: ACM, 2018, pp. 2:1–2:6.

[13] G. Bianchi, “Performance analysis of the IEEE 802.11 distributed coordination function,” *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, 2000.