Thesis for Master of Engineering

Bio-Inspired Congestion Control Mechanism in Industrial Internet of Things

June 2018

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Kumoh National Institute of Technology

Department of IT Convergence Engineering

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Abstract

Congestion in a network is determined by the resource constraints and the number of deployed sensor nodes. Congestion can significantly degrade the quality of services (QoS) regarding throughput and end-to-end delay. In this thesis, a hybrid bio-inspired algorithm is proposed for congestion control in large-scale Industrial IoT that necessitate controlled performance with graceful degradation. Each algorithm overcomes each other drawback. First, a competitive Lotka-Volterra (C-LV) model to avoid congestion is employed by regulating the rate of each traffic flow, while fairness among sensor nodes is maintained. However, parameters of C-LV need to be optimized. Thus, dragonfly algorithm (DA) is employed to enhance C-LV by optimizing the

parameter for minimizing end-to-end delay. DA makes this scheme adaptive to change and get optimized parameter when there is change number of node due to new installation or faulty node. Performance evaluations verify that the proposed scheme improves the QoS in IIoT environment and achieves adaptability to changing traffic loads, scalability and fairness among flows while providing graceful performance degradation as load increases.

대규모 산업용 IoT 환경에서의 생체모방 혼잡 제어 기법

Muhammad Royyan

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요약

본 논문에서는 대규모 IIoT(Industrial IoT) 환경에서 혼잡 제어를 위한 복합 생체 모방 알고리즘을 제안한다. 네트워크의 혼잡은 한정된 자원과 센서 노드의 수에 의해 발생되며 처리량 및 end-to-end 지연에 관련된 QoS(Quality of Service)를 저하시킬 수 있다. 제안하는 알고리즘은 이러한 네트워크 혼잡을 피하기 위해 다음과 같은 방식을 사용한다. 첫째, C-LV(Competitive Lotka-Volterra) 모델을 사용하여 각 트래픽의 속도를 조절하며, 노드 간의 공정성을 유지한다. 하지만 C-LV 의 매개 변수의 최적화가 요구된다. 둘째, DA(Dragonfly Algorithm) 은 end-to-end 지연을 최소화하기 위한 변수를 최적화하여 C-LV 의 성능을 향상시킨다. DA 는 새로 설치되거나 고장 노드로 인해 노드의 개수가 변경되면 제안하는 기법을 변경하고, 최적화된 변수를 얻을 수 있도록 한다. 시뮬레이션 결과들은 제안된 기법이 IIoT 환경에서 QoS 를 향상시키고, 플로우 간에 변화하는 트래픽 부하, 확장성 및 공정성에 적응할 수 있음을 보여준다. 또한 제안하는 기법이 부하가 증가함에 따라 성능저하를 완화시킴을 확인하였다.

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List of Nomenclatures

6LoWPAN	:	Low Power Wireless Perseonal Network with IPv6
6TiSCH	:	TSCH with IPv6
AIMD	:	Additive Increase Multiplicative Decrease
ARC	:	Adaptive Rate Control
CA	:	Collision Avoidance
CCF	:	Congestion Control and Fairness
CDU	:	Channel Distribution and Usage
C-LV	:	Competitive Lotka-Volterra
CODA	:	Congestion Detection and Avoidance
CSMA	:	Carrier-Sense Multiple Access
DA	:	Dragonfly Algorithm
ECODA	:	Enhanced Congestion Detection and Avoidance
FACC	:	Fairness-Aware Congestion Control
HART	:	Highway Addressable Remote Transducer Protocol
IIoT	:	Industrial IoT
IoT	:	Internet of Things
IP	:	Internet Protocol
IT	:	Information Technology
OT	:	Operational Technology
PAN	:	Personal Area Networks
PERA	:	Purdue Enterprise Reference Architecture
QoS	:	Quality of Service
RPL	:	Routing Protocol for Low-Power and Lossy Networks
TSCH	:	Time-slotted Channel Hopping
WSN	:	Wireless Sensor Networks

Acknowledgment

Thanks to Allah for giving me this opportunity, the strength and the patience to complete my thesis finally, after all the challenges and difficulties.

First and foremost, I would like to express my most enormous gratitude to my supervisor Professor Dong-Seong Kim, who have guided and helped me a lot throughout this thesis process. He has been supportive since the days I began working at NSL as a Master student. He helped me come up with the thesis topic and steered me in the right direction whenever he thought I needed it. During the most challenging times when writing this thesis, he gave me the moral support and the freedom I needed to move on. This appreciation is also dedicated to all NSL members, those who are generous and helpful.

I also would like to express my warmest and sincerest appreciation to my beloved wife, Rufaidah for her patience, assistance, continuous support and understanding in everything I did. Not to forget, an apple of our eyes, Wafi Royyan Zahir.

Hopefully, this master's thesis will not be the end of my journey in seeking for more knowledge to understand the meaning of life.

Gumi, 8 June 2018

Muhammad Royyan Zahir

Chapter 1 Introduction

1.1 Overview and Trends

WSNs are wireless networks consisting of spatially distributed autonomous nodes using sensors to monitor physical conditions [1–4]. A rapidly increasing range of WSNs are now applied in health monitoring and, military surveillance, and they are especially widely used in industrial systems [5, 6]. With the emergence of the Internet of Things (IoT), WSN becomes more exciting, and until today the unstoppable evolution can be witnessed [7, 8]. Through IoT, anything or anyone can be connected anytime and anywhere. Recently, Industrial and IP-enabled low-power wireless technologies are emerging, and resulting Industrial IoT (IIoT). When IIoT network is controlled correctly [9, 10], it provides reliability, scalability, interoperability, and economic benefits due to eliminating much wire.

Steel mills, oil refineries, and offshore drilling platforms implement complex industrial processes, which require tight control and a scalable diagnostic transport. Thousands of sensing points are used to report temperature, pressure, and tank fill levels to an industrial process control center. This center, either in an automated way or through human intervention, uses that information to control an actuator, start a new production stage, scheduled maintenance, or trigger an alarm. Communication between sensors, actuators, and the control center is done through an industrial network. This class of network needs to offer ultra-high reliability while operating reliably in harsh environments. Network failures can have catastrophic consequences and are therefore not an option. To gain higher security and reliability, an industrial network is classically partitioned in a hierarchical manner per the Purdue Enterprise Reference Architecture (PERA), using different technologies at each level, and wireless networks are used at the last hop(s) to the field devices. Industrial networking technology has developed over the last 40 years to satisfy those requirements. A dominant industrial standard is HART [11], a set of standards covering the protocol, connectors, and wires interconnecting the different networked elements. Depending on the safety regulations in use, the price of drawing cables across an industrial plant can run from $100s/ft to $1,000s/ft. Planning, installing, and maintaining these cables represent a significant portion of the cost of ownership of such a wired industrial network. As detailed in this article, advances in reliable wireless technology enable low-power wireless networks to exhibit 99.999% end-to-end reliability and a decade of battery lifetime [12], making them a suitable alternative to wires. This has triggered a trend for, industrial networks to "go wireless."

The development of IIoT is a factor in the convergence between traditional networks and industrial networks, namely IT/OT convergence [13,14]. Where, operational technology (OT) refers to industrial networks which focus on reliable and deterministic networking. In addition, information technology (IT) refers to the Internet. To sum up, the purpose of the IT/OT convergence is to cover OT drawback using IT technologies, for instance, the use of big data/analytic scheme on an enormous amount of data to optimize industrial processes. To enable IT/OT convergence over a shared network, components to allow IPv6 over medium access technologies such as IEEE 802.15.4e TSCH need to be provided. Therefore, the new 6TiSCH working group was created to enable IPv6 over TSCH mode of IEEE 802.15.4e standard.

1.2 Background

1.2.1 Timeslotted Channel Hopping (TSCH)

IEEE 802.15.4e MAC layer amendments [15] are introduced to the original 802.15.4 MAC [16] with enhanced functionality to support industrial Internet applications that can be realized using Time-slotted Channel Hopping (TSCH). The medium access is achieved in TSCH mode using slotted CSMA/CA scheme ensuring utterly deterministic access time, unlike the shared CSMA/CA access. The nodes in TSCH Personal Area Networks (PANs) can work in a star topology as well as mesh topologies. In TSCH network, time is divided into timeslots sufficient enough to transmit a single frame and receive an optional acknowledgment. A slot-frame is a group of time-slots that repeats over time giving the opportunity for devices to perform their communication schedule through send & receive with neighbor devices or power-saving sleep cycle. The higher layers are responsible for configuring the number of time slots in a slot-frame, in effect creating a communication schedule. Channel hopping supported in TSCH mode enables several concurrent slot-frames to be present exploiting the use of multiple frequencies for communication to avoid multi-path fading and interference. Devices communicate in one or more slot-frames in parallel but using different channel offset.

1.2.2 IPv6 over IEEE TSCH mode

In IETF 6TiSCH architecture, 6TiSCH Operation Sublayer (6top) [17] is a Logical Link Control layer between 6LoWPAN and TSCH MAC layer as shown in Fig. 1.1. 6top provides set of interfaces/commands to upper 6LoWPAN & RPL layers supporting: (i) creation of cell schedule for slot offset and channel offset (ii) transfer of data to TSCH once the schedule is established (iii) retrieval of status information for management & monitoring.

The primary functionality provided by 6TiSCH is the support for scheduling transmissions of IPv6 packets by ensuring the provision of schedule time to devices that are free from contention. The time and frequency in 6TiSH architecture are given in the form of Channel Distribution and Usage (CDU) matrix [18–21] with columns representing the number of available channels (accessed by ChannelOffset) while the rows are divided into group of timeslots (accessed by SlotOffset) used in network scheduling operation. The timeslot duration of each cell typically in 802.15.4e is of the order of 10 to 15 milliseconds long enough for packet transmission and acknowledgment. A slotframe consists group of equal length timeslots and a node schedule can involve multiple slotframes simultaneously with different activities scheduled in different slot frames. In our experiments, we have considered 6TiSCH default scheduling available as part of OpenWSN and customized for 3, 6 and 9 slot schedules.

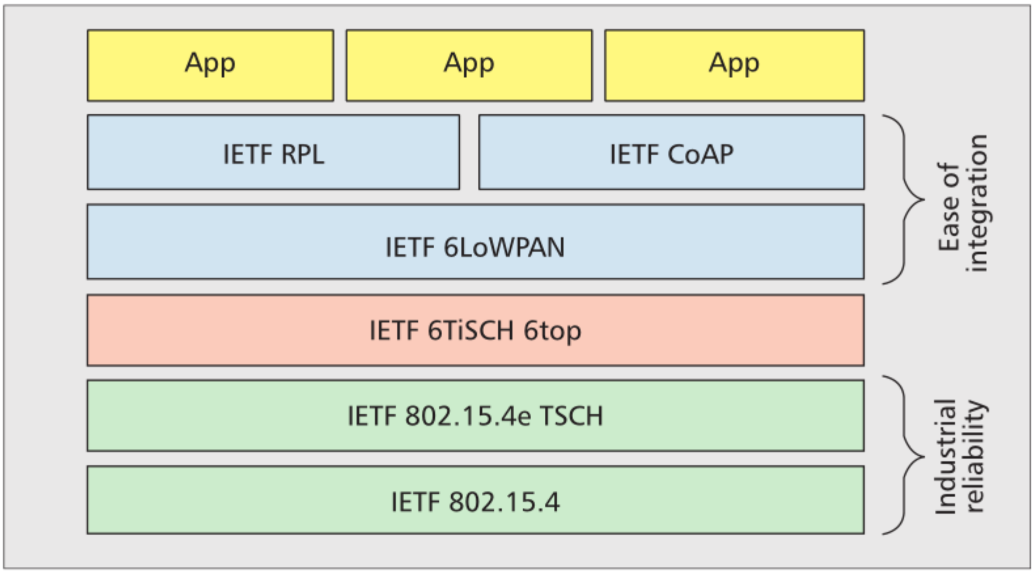


Figure 1.1: The protocol stack for the IIoT

1.2.3 Congestion Control

However, in a large-scale network, congestion becomes one of the significant problems which can prevent IIoT to work appropriately. Resource constraints, high traffic-load, and the high numbers of deployed sensors lead to network congestion [22], which occurs when the transmitted packet load exceeds the available buffer capacity at any given time. This could lead the degradation of the network's quality of service (QoS), characterized by low throughput, long delay, and increased packet loss. Moreover, a harsh condition in the Industrial environment makes it prone to congestion. Hence, controlling congestion is a significant challenge in IIoT.

Due to the event-driven nature of WSNs, resource constraints, many-to-one communications, number of deployed sensors and the high traffic of sensor nodes lead to the creation of congestion in these networks. In

WSNs, network congestion occurs when the offered traffic load exceeds the available capacity at any point in the network [23]. Indeed, it can be mentioned that congestion is one of the highly critical challenges in WSNs and it has a profound impact on QoS parameters and the energy efficiency of sensor nodes. Moreover, congestion increases packet loss and degrades the throughput or wireless channels. Thus, to handle such challenges and problems in WSNs, researchers should consider and control the factor of congestion as shown in Fig. 1.2.

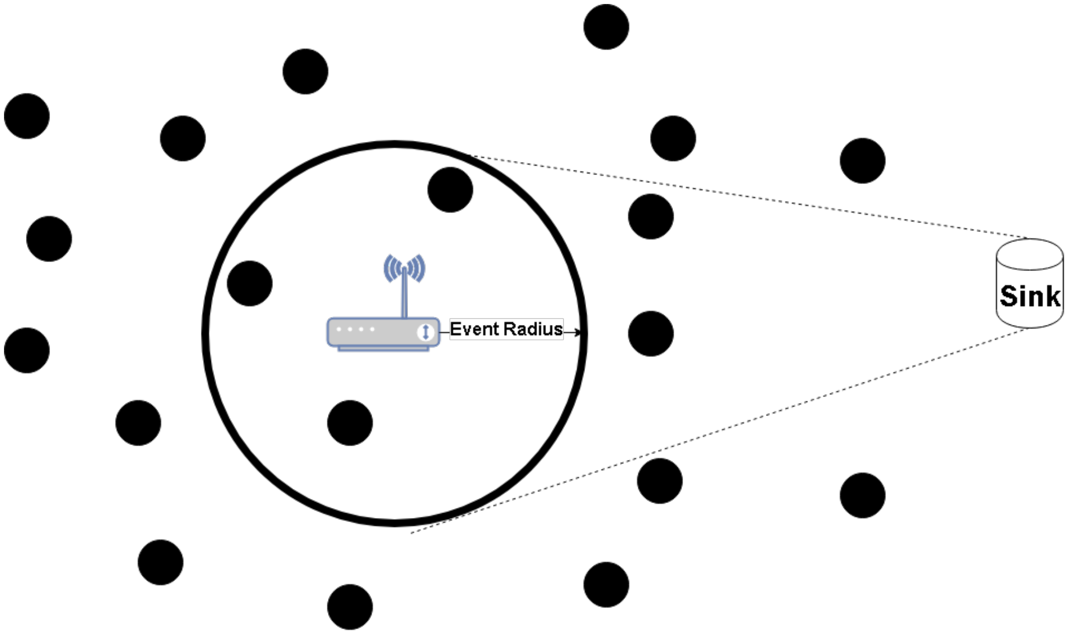


Figure 1.2: Many-to-one data transmission scheme

Fig. 1.3 illustrates congestion in WSNs is created at two levels: node-level congestion (or buffer overflow) and link-level congestion. In node-level congestion, when packet arrival rate is higher than packet service rate, congestion is caused. This type of congestion occurs mostly in those sensor nodes which are closer to the sink. Node-level congestion increases packet loss and power waste in WSNs. Consequently, this type of congestion has a direct impact on network availability and network lifetime. Factors such as competition, collision and bit error result in link-level congestion. Thus, in this kind of congestion, packet delivery rate in sink node is reduced. Therefore, for enhancing throughput and packet delivery rate at the sink node, collision should be prevented by using an appropriate medium access control based congestion control algorithms.

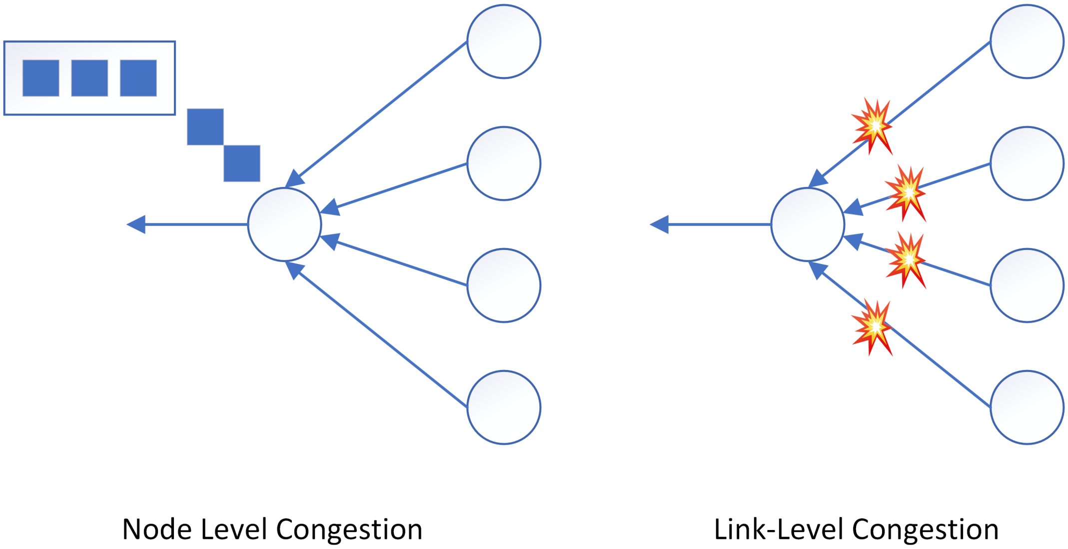


Figure 1.3: Common congestion positions

1.3 Related Works

The conventional method for mitigating congestion namely additive increase multiplicative decrease (AIMD) [24]. AIMD checks the available buffer capacity through slow enhancement of congestion detection condition. When congestion is detected, the protocol decreases the congestion window significantly. Through this scheme, congestion is reduced. However, AIMD provokes a saw-tooth-like rate which violates the QoS. Besides, AIMD scheme takes a long time for data rates to converge.

Woo et al. [25] introduced the Adaptive Rate Control protocol which was aimed at monitoring the injection of packets into the traffic stream as well as route-through traffic. In ARC, each node estimates the number of upstream nodes and the bandwidth is split proportionally between a relay and locally-generated traffic; however, the preference is given to the former. In ARC, in case an intermediate node overhears that the packets it sent previously are successfully forwarded again by its parent node, it will increase its rate by the constant α. Otherwise, it will multiply its rate by a factor β where $0 < \beta < 1$. ARC does not explicitly detect congestion and does not notify congestion explicitly; thus, it avoids using control messages. ARC improves fairness and is considered to be an energy-efficient congestion control algorithm for WSNs. However, it should be pointed out that ARC rate adjustment scheme introduces packet loss.

Wan et al. [26] proposed congestion detection and avoidance (CODA) protocol for controlling congestion in WSNs. CODA amalgamated the present and past channel load and the level of buffer load to detect congestion at the intermediate sensor nodes. This protocol makes use of two strategies to control congestion: open-loop hop-by-hop backpressure and closed-loop multi-source traffic regulation. In open-loop hop-by-hop backpressure used for transient congestion, a node broadcasts back-pressure messages up-stream towards source nodes to reduce their transmission rates. In closed-loop multi-source regulation which is based on end-to-end acknowledgment and is used for persistent congestion, the sink asserts congestion control over many source nodes. To regulate data transmission rate, sink node transmits ACK packets towards nodes. In CODA, control packets such as ACK and backpressure consume the additional energy of the sensor nodes. CODA does not provide flow fairness and differentiates services into multiple classes of traffic. CODA adjusts rate through AIMD mechanism which often leads to packet loss. CODA carries out unidirectional congestion control, increases timelines but does not consider reliability.

In congestion control and fairness (CCF) protocol [27], congestion detection depends on packet service time, and every sensor node controls the rate of its downstream nodes. This method uses a scalable and distributed algorithm to conduct upstream congestion control which ensures the fair delivery of the packets to the central station as well as congestion elimination. CCF formulates congestion control and determines the number of downstream nodes, an average transmission rate of the packets and the production rate in each sensor. CCF precisely adapts traffic rate according to packet service time and fair packet scheduling algorithms. CCF controls congestion hop-by-hop, and each node uses precise rate adjustment based on available service rate and child node number. Rate adjustment in CCF is a function of packet service time which can result in low utilization when some sensor nodes do not have enough traffic or significant packet error rate. However, CCF does not take current queue utilization into account which results in the increased queuing delays, and various buffer overflows as well as increased retransmissions.

Hull et al. [28] introduced Fusion as a method for mitigating congestion; this method detects congestion through queue lengths. Moreover, Fusion makes use of hop-by-hop flow control, rate limitation and a prioritized MAC technique to handle congestion. If the packets of nodes are intended to be dropped downstream, hop-by-hop flow control stops them from transmitting packets because of insufficient buffer spaces. When compared with other uncongested nodes, it is observed that this priority is accomplished through decreasing the random back-off timer of congested nodes. Rate limitation metrics of traffic are accepted into a network to prevent unfairness towards sources located far from the sink. A prioritized CSMA-based MAC ensures that the congested nodes should receive prioritized access to the channel. As a result, it should be maintained that FUSION optimizes fairness and has a good throughput; nevertheless, it is only useful in case all nodes have the same traffic load [29]. Moreover, fusion is not able to guarantee an optimal transmission rate for those nodes which are both fair and efficient.

Vedantham et al. [30] proposed an adaptive, explicit rate control method, referred to as congestion control from sink to sensors (CONSISE). This method adjusts the downstream transmission rate at each of the sensor nodes to utilize the available network bandwidth. It should be noted that CONSISE is regarded as a highly scalable and easily implementable method which has remarkable performance advantages; that is, it uses resources efficiently with minimal overheads. In CONSISE, as a node receives a packet from an upstream node, it will piggyback the respective information based on its current transmission rate and its node identifier. Moreover, as each downstream node receives a packet, it updates the information for the number of packets received from a specific node. At the expiry of a periodic timer, a node specifies its transmission rate and gives explicit feedback to the upstream node. Scheuermann et al. [31] put forth a hop-by-hop congestion control protocol designed for the unique features of the shared medium. This proposed congestion control protocol ensures that changing common conditions are replied rapidly and that the overhead is negligible.

Yin et al. [32] proposed Fairness-Aware Congestion Control (FACC) which is intended to control congestion and maintain approximately fair bandwidth allocation for different flows. Near-source nodes maintain a per-flow state and allocate an approximately fair rate to each passing flow. In contrast, near-sink nodes do not have to keep a per-flow state and use a lightweight probabilistic dropping algorithm according to queue occupancy and hit frequency. Indeed, it can be mentioned that FACC optimizes throughput, packet loss, energy efficiency and fairness.

CADA. Fang et al. [33] presented a scheme for congestion avoidance, detection and alleviation (CADA) in WSNs. This scheme optimizes energy consumption and information loss problems. By exploiting data features, a few representative sensor nodes are selected from those in the event area as data sources: as a result, source traffic can be mitigated and controlled pro-actively. Consequently, the potential congestion is avoided. When congestion takes place unavoidably as a result of traffic emergency, it will be detected immediately by the hot spot node based on a combination of buffer occupancy and channel utilization. Moreover, congestion is alleviated reactively by either dynamic traffic control or source rate regulation according to specific hot spot scenarios. In other words, it can be mentioned that CADA optimizes throughput, energy consumption, and average end-to-end delay.

Enhanced congestion detection and avoidance (ECODA) was developed to use dual buffer thresholds and weighted buffer difference for detecting congestion in WSNs [34]. ECODA includes three mechanisms: (1) in the first strategy, dual buffer thresholds and weighted buffer difference are used as to detect congestion; (2) the second strategy makes use of flexible queue scheduler based on packet priority; (3) the control scheme of bottleneck node-based source transmission rate is used as the third strategy in case of persistent congestion. Indeed, ECODA uses hop-by-hop congestion control scheme for transient congestion. Brahma et al. [35] put forth a distributed congestion control algorithm for tree-based communications in WSNs; this algorithm assigns a fair and efficient transmission rate to each node. Also, each node controls and monitors its aggregate output and input traffic rate. For the difference between input and output traffic rate, a node decides on whether to increase or decrease the bandwidth; such a decision to increase or decrease the bandwidth is allocated to the flow that originates from itself and its neighboring nodes.

Domingo et al. [36] introduced bio-inspired congestion control for underwater WSNs. This algorithm differentiates packet losses due to congestion from packet losses related to high link error rates. It provides flow fairness, but it does not guarantee reliability which is vital in IIoT.

A recent bio-inspired congestion control scheme was introduced that mimics the flocking of birds [37]. Bird behavior was used as a basis to design a robust, scalable, and decentralized congestion control scheme for WSNs. By moving packets to the sink and exploiting available network resources, the load is balanced. Moreover, flock-CC can reduce packet loss with various traffic load conditions. However, this scheme does not address fairness since not all sensor nodes can have same chance to transmit their packet load.

Previous work on congestion control involving mathematical models of population biology was proposed for the Internet by either improving the current TCP CC mechanism [38] or providing a new way of combating congestion [39]. The study of [38] couples the interaction of Internet entities that are involved in CC mechanisms (routers, hosts) with the predator-prey interaction. This model exhibits fairness and acceptable throughput but slow adaptation to traffic demand. Recent work by Hasegawa et al. [39] focuses on a new TCP CC mechanism based on the LV competition model which is applied to the congestion window updating mechanism of TCP. According to the authors, remarkable results regarding stability, convergence speed, fairness, and scalability are exhibited. However, these approaches are based on the end-to-end model of the Internet.

1.4 Motivation and Contributions

In this thesis, a hybrid of two bio-inspired algorithms for congestion control is investigated. The first one is a competitive Lotka-Volterra (C-LV) model [40,41]. By using C-LV, congestion avoidance can be guaranteed. It is a decentralized scheme that controls the rate of transmission to prevent congestion while achieving fairness among all sensor nodes. The primary objective of using C-LV is to provide efficient and smooth rate adaptation while avoiding congestion in traffic and maintaining fairness. C-LV provide a coexistence solution by adequately choosing the parameters to guarantee congestion-free traffic. However, appropriately choosing parameters could be time-consuming and seemingly impossible if there is an enormous number of nodes. To address this problem the second bio-inspired algorithm in this thesis is introduced.

The second proposed algorithm is the dragonfly algorithm (DA) [42]. In the C-LV model, there are critical parameters that must be appropriately chosen. DA can be employed to carry out this task. In addition to avoiding congestion and maintaining fairness, DA enhances the C-LV scheme by optimizing the transmission rate. With throughput as the objective function of DA, agents find a solution with the objective of minimizing delay as much as possible. Unlike gradient descent, DA is not prone to be trapped in a local optimum solution and has a high chance achieving a global optimum solution. By combining these two algorithms, congestion-free traffic with fairness and the lowest possible end-to-end delay is achieved without the need to choose critical parameters manually.

The contributions of this thesis are summarized as follows:

1. Hybrid bio-inspired algorithms for congestion control in large-scale IIoT are introduced.

2. Due to the decentralized nature of the scheme, the overhead is mini-

mized.

3. The C-LV scheme guarantees congestion-free traffic and maintains fairness for each sensor node.

4. The DA enhances the C-LV model by providing an optimal parameter for minimizing end-to-end delay as much as possible.

5. The adaptive nature of the scheme helps the system to adapt to changes such as an increased or decreased number of the sensor nodes during operation.

The simulation results verify that the proposed scheme guarantees congestion-free traffic and maintains fairness among sensor nodes. A packet load is transmitted as fast as possible without causing congestion. Moreover, the simulation results demonstrate the adaptiveness of the scheme in responding to dynamic change.

The remainder of this thesis is organized as follows. In Chapter II, the overview of C-LV and DA is presented in detail, and the proposed Bio-inspired congestion control mechanism for IIoT is elaborated. In Chapter III, the simulation results are presented. Finally, Chapter IV presents the conclusions and directions for future work.

Chapter 2 System Model

2.1 C-LV Model

The change of population's size of particular species as the result of species interaction with resources and competitors can be modeled and predicted over time by differential equations. C-LV is the most famous mathematics model of population dynamics. C-LV model describes a relationship between species competing for the shared resource.

Assuming that all the parameters in the model are positive, the generalized C-LV model of n-species can be expressed by ordinary differential equations (ODE):

$$\frac{dx_i}{dt} = r_i x_i \left(1 - \frac{\sum_{j=1}^{n} \alpha_{ij} x_j}{K_i}\right), \ \forall i \in \{1, 2, 3, ..., n\}, \tag{2.1}$$

where $x_i(t)$ is the population size of species i at time t, and r_i is the intrinsic growth rate in the absence of all other competing species. It should be noted that, every species cannot produce offspring without having initial population, i.e. $x_i(0) > 0, \ \forall i \in \{1, 2, 3, ..., n\}$. Here, K_i is the maximum population of species i in the absence of all other species, that is, the carrying capacity. Moreover, α_{ij} denotes effect of the species j's population on the growth of species i. Note that α_{ii} denotes the effect of species i's population on the growth of its own species. In this thesis, α_{ii} is denoted as β_i. Through Eq. (2.1), it can be determined that the maximum number of species i is K_i/β_i. When $\beta_i > \alpha_{ij}, \forall i, j \in \{1, 2, 3, ..., n\}$ and $i \neq j$, the effect of population's size of species i to its own growth is greater than the effect of species j on population dynamic of species i. The explanations of notations that are used in this thesis are shown in Table 2.1.

Table 2.1: Notation

Notation	Definition
t	time
x_i	Number of species i
r_i	Intrinsic growth rate of species i
K	Capacity
α_{ij}	effect of the species j's population on the growth of species i
β_i	effect of the species i's population on the growth of its species
n	Number of species

According to analytical studies [43], the final state can be one of the following states:

1. All species can coexist.

2. At least one species can survive, and other species become extinct.

Eq. (2.1) cannot be precisely solved. However, the behavior of its solution can be calculated. Through phase plane analysis, the outcome of competition can be predicted. Based on the trajectories of the solutions, the dynamic path can be determined.

When solving a non-linear differential equation such as Eq. (2.1), an approximate solution is needed to reduce computational complexity. Linearizing is one of an approximate method. The equilibria are constant solutions that make the system converges. The equilibria is solutions that make $dx_i/dt = 0$ is satisfied $\forall i \in \{1, 2, ..., n\}$. Hence, it is better to investigate their stability through linearizing solution near the equilibria.

It is denoted that $X^* = (x_1^*, x_2^*, ..., x_v^*)$ as vector of solution of $dx_i/dt = 0$. A stable solution is if every solution X^*, make $(x_1(t), x_2(t), ..., x_n(t)$ remain close to the equilibrium $\forall t \geq 0$. An equilibrium X^* is asymptotically stable if it is stable and $(x_1(t), x_2(t), ..., x_n(t)$ converge to the equilibrium as $t \rightarrow 0$. The eigenvalues of matrix that consist of coefficients of variables of the linearized system can determine the stability. Asymptotically stable can be achieved if only if all eigenvalues have negative real part. Brauer et al. [43] said that in C-LV, the stability of the equilibrium depends on value of α and β.

2.2 Dragonfly Algorithm

The DA algorithm is inspired by static and dynamic swarming behaviors. These two swarming behaviors are very similar to the two main phases of optimization using meta-heuristics: exploration and exploitation. Dragonflies create sub-swarms and fly over different areas in a static swarm, which is the main objective of the exploration phase. In the static swarm, however, dragonflies fly in bigger swarms and along one direction, which is favorable in the exploitation phase.

The behavior of swarms follows three primitive principles [42]:

- **Separation**

  The static collision avoidance of the individuals from other individuals in the neighborhood.

- **Alignment**

  Velocity matching of individuals to that of other individuals in the neighborhood.

- **Cohesion**

  The tendency of individuals towards the center of the mass of the neighborhood.

The goal of any swarm is survival by finding resources and avoiding predators. Therefore, in DA there are five factors to construct a mathematical model for an individual position. Each of this factor can be modeled as follows:

- **Separation**

  $$S_i = -\sum_{j=1}^{N} X - X_j, \tag{2.2}$$

  where X is the current position of individual, and Xj is the position j^{th} neighboring individual, moreover N is the number of neighboring individuals.

- **Alignment**

  $$A_i = \frac{\sum_{j=1}^{N} V_j}{N}, \tag{2.3}$$

where V_j is the velocity of j^{th} neighboring individual.

- **Cohesion**

$$C_i = \frac{\sum_{j=1}^{N} X_j}{N} - X. \tag{2.4}$$

- **Attraction to food**

$$F_i = X^{+} - X, \tag{2.5}$$

where X^{+} is the position of the food. In DA, food position is chosen from best solutions.

- **Distraction from enemy**

$$E_i = X^{-} + X, \tag{2.6}$$

where X^{-} is the position of the enemy. In DA, enemy position is chosen from worst solutions.

The movement of dragonflies is constructed from these five patterns. DA is developed based on the framework of the PSO [44,45]. In DA, each dragonflies' position represents a possible solution to optimizing group the objective, which is denoted by objective function $f(x)$. The position starts with the random initialization. The vector of position and the vector of velocity can be indicated as $X = (x_1, x_2, x_3, ..., x_N)$ and $V = (v_1, v_2, v_3, ..., v_N)$, respectively, where N is the number of dragonflies. Then, the velocity and position of the particles are updated periodically according to following equations:

$$V(t+1) = (sS_i + aA_i + cC_i + fF_i + eE_i) + wV(t), \tag{2.7}$$

$$X(t+1) = X(t) + V(t+1), \tag{2.8}$$

where s, a, c, f, e, and w are separation weight, alignment weight, cohesion weight, food factor, enemy factor, inertia weight respectively. To increase chance to converge to optimized values, weights are change randomly each iteration.

To improve stochastic behavior, when there is no neighboring solution dragonflies fly around using a random walk (Levy flight). When this occurs, a position of dragonflies is updated using:

$$X_{t+1} = X_t + Levy \times X_t, \tag{2.9}$$

where the Levy flight is determined by [46]:

$$Levy = 0.01 \times \frac{r_1 \times \sigma}{|r_2|^{\frac{1}{\beta}}}, \tag{2.10}$$

where r_1, r_2 are two random number such that $r_1, r_2 \in [0, 1]$. And β is constant where in this case $\beta = 1.5$. Moreover, σ is determined by:

$$\sigma = \left(\frac{\Gamma(1+\beta) \times \sin(\frac{\pi\beta}{2})}{\Gamma(\frac{1+\beta}{2}) \times \beta \times 2^{\frac{\beta-1}{2}}} \right)^{1/\beta}, \tag{2.11}$$

where $\Gamma(x) = (x-1)!$.

Chapter 3 Proposed CC Mechanism in IIoT

3.1 Proposed C-LV for Congestion Control in IIoT

In this thesis, we design congestion control scheme based on the deterministic information of population dynamics from C-LV. An IIoT has some similarities with an ecosystem. An ecosystem consists of several species that live together and interact with resources to survive and coexist. In IIoT, before forwarding data to the Internet, each sensor node has to compete to transmit their payload to the sink node through a harsh industrial environment. IIot consists of sensor nodes that work cooperatively. Each node has a buffer, and the number of the available buffers can cause traffic flow to be initiated differently. In the C-LV model, traffic flows can be seen as species that compete for available network resources. Moreover, the number of bytes per traffic flow can be seen as the population of each traffic flow. The purpose of implementing C-LV model in IIot is designing a scheme to guarantee the coexistence of the flows as an ecosystem tries to make sure each species coexists.

The proposed scheme provides rate adaptation by regulating the traffic flow rate at each sensor node. Therefore, each sensor node controls the rate of its traffic flow. Owing to the decentralized nature of the proposed scheme, it needs low communication overhead.

As shown in Fig. 3.1, each sensor node sends a packet to the sink node. Each node acts as a competing species, and the buffer capacity of the sink node can be seen as the carrying capacity of every species. Therefore, each traffic flow has the same carrying capacity in this model, i.e.,

$$\forall i \in \{1,2,3,...,n\},\ K_i = K. \tag{3.1}$$

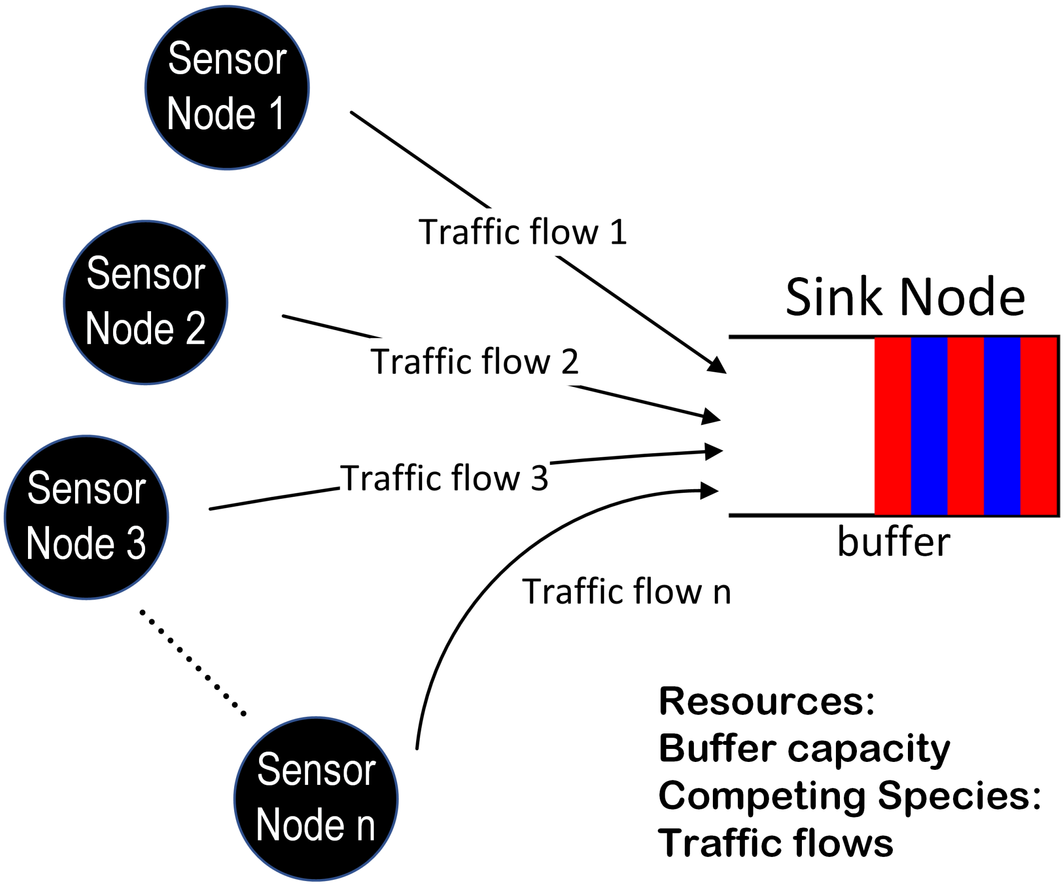


Figure 3.1: Traffic flows competition in WSNs

In this scheme, for simplicity, it is assumed that

$$\forall i,j \in \{1,2,3,...,n\},\ \alpha_{ij} = \alpha,\ \text{when } i \neq j, \tag{3.2}$$

$$\forall i \in \{1,2,3,...,n\},\ \alpha_{ii} = \beta, \tag{3.3}$$

and

$$\forall i \in \{1, 2, 3, ..., n\},\ r_i = r. \tag{3.4}$$

Therefore, the transmission rate of each traffic flow is determined periodically by,

$$\frac{dx_i}{dt} = rx_i(1 - \frac{\beta}{K}x_i - \frac{\alpha}{K}C_i),\ \forall i \in \{1, 2, 3, ..., n\}, \tag{3.5}$$

where, $C_i = \sum_{j=1, j\neq i}^{n} x_j$.

Moreover, the solution of Eq. (3.5) is

$$x_i(t) = \frac{wx_i(0)}{\beta x_i(0) + [w - \beta x_i(0)]e^{-\frac{wr}{K}t}},\quad w = K - \alpha C_i. \tag{3.6}$$

In this thesis, two topologies are investigated. As shown in Fig. 3.2 and Fig. 3.3, they are star topology and mesh topology.

In the case of the star topology, the scheme is simple. The transmission rate of each sensor is calculated from Eq. (3.6) which is the solution of Eq. (3.5). To calculate $x_i(t)$ from Eq. (3.6), C_i should be determined. In this thesis, C_i is the total number of bytes sent from all another node which compete with node i. As shown in Fig. 3.4 and Fig. 3.5, after receiving data from the lower level node, parent nodes broadcast information regarding a total number of bytes sent (BS) from all lower nodes. Therefore, C_i can be calculated by subtracting its transmission rate from BS.

For mesh topology Fig.3.3, slight modification is needed. The previous method can be applied for transmitting data from sensor node (SN) to their cluster head (CH). In this thesis, CH does not generate any packets, but forwarding packets from SN into the sink node. In another word, CH multiplex all incoming data and relay it to the sink node. The transmission rate of CH when transmitting to the sink node can be determined by:

$$x_{CH_i}(t) = m_{CH_i} \times (\frac{wH_i(0)}{\beta H_i(0) + [w - \beta H_i(0)]e^{-\frac{wr}{K}t}}), \tag{3.7}$$

where $w = K - \alpha C_{CH_i}$, $H_i(0) = \frac{x_{CH_i}(0)}{m_{CH_i}}$ and $C_{CH_i} = BS - H_i(0)$. In this case, m_{CH_i} is number of SN that transmit to CH_i. For instance, in Fig. 3.3, $m_{CH_i} = 4$, $\forall i \in \{1, 2, 3, 4\}$. As long as routing of WSN is predefined, same method as above can be applied to scale up the topology complexity.

3.2 C-LV Stability Analysis

The stability analysis of C-LV has been investigated in literature [47]. Without loss of generality, Eq. (3.5) can be expressed in vector form by:

$$\frac{dx_i}{dt} = X(\overrightarrow{\mathrm{b}} - A\overrightarrow{\mathrm{x}}), \tag{3.8}$$

where $\overrightarrow{\mathrm{x}} = (x_1, ..., x_n)^T$ is an n-dimensional vector, $X = diag(x_1, ..., x_n)$ is an $n \times x$ diagonal matrix, $\overrightarrow{\mathrm{b}} = (b_1, ..., b_n)^T$ is an n-dimensional vector, and

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \dots & a_{1j} \\ a_{21} & a_{22} & a_{23} & \dots & a_{2j} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & a_{i3} & \dots & a_{ij} \end{bmatrix}$$

is $n \times n$ matrix.

In this thesis, $\mathbb{R}^n$ is denoted as n-dimensional Euclidean space. Let $Q = \{q|q \in (1, ..., n),\ x_i^* = 0\ \forall i \in Q\}$, where $\overrightarrow{\mathrm{x}^*} = (x_1^*, ..., x_n^*)$ is a non-negative equilibrium solution of Eq.(3.5). Let $P = N - Q$ such that $x_p^* > 0\ \forall p \in P$. As set corresponding to $\overrightarrow{\mathrm{x}^*}$, $\mathbb{R}_Q^n$ can be defined as

$$\mathbb{R}_Q^n = \{x|x \in \mathbb{R}^n,\ x_q \geq 0\ \forall q \in Q \cap\ x_p > 0\ \forall p \in P\}.$$

Definitions and a theorem related to stability are provided,

Definition 1 If A is an $n \times n$ real matrix, $A \in S_W$ means that there exists an $n \times n$ positive definite diagonal matrix W such that $WA + A^T W$ is positive definite.

Theorem 1 Matrix A is positive definite if and only if all its eigenvalues are positive.

Definition 2 A non-negative equilibrium solution $\overrightarrow{\mathrm{x}^*}$ of Eq. (3.5) is called asymptotically stable with respect to $\mathbb{R}_Q^n$ if only if:

- The equilibrium solution $\overrightarrow{\mathrm{x}^*} \geq 0$ is stable respect to $\mathbb{R}_Q^n$, if $\forall \epsilon > 0$, $\exists \delta(\epsilon)$ such that when $|\overrightarrow{\mathrm{x(0)}} - \overrightarrow{\mathrm{x}^*}| < \delta(\epsilon)$, then $|\overrightarrow{\mathrm{x(t)}} - \overrightarrow{\mathrm{x}^*}| < \epsilon,\ \forall t \geq 0$.
- Each equilibrium solution converges to $\overrightarrow{\mathrm{x}^*}$ as $t \to +\infty$

As it is investigated in [48], if $A \in S_W$, then Eq. (3.7) has non-negative and stable (respect to Definition 2) equilibrium solutions $\forall b_i \in \mathbb{R}^n$. In this thesis, as mention in previous section, it is assumed for simplicity in Eq.

(3.1), Eq. (3.2), Eq. (3.3), and Eq. (3.4). Based on those, matrix and vector A and $\overrightarrow{\mathrm{b}}$ of Eq. (3.7) can be constructed as:

$$
\begin{aligned}
A &= \begin{bmatrix} \frac{\beta r}{K} & \frac{\alpha r}{K} & \frac{\alpha r}{K} & \dots & \frac{\alpha r}{K} \\ \frac{\alpha r}{K} & \frac{\beta r}{K} & \frac{\alpha r}{K} & \dots & \frac{\alpha r}{K} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \frac{\alpha r}{K} & \frac{\alpha r}{K} & \frac{\alpha r}{K} & \dots & \frac{\beta r}{K} \end{bmatrix} \\
&= \frac{r}{K} \begin{bmatrix} \beta & \alpha & \alpha & \dots & \alpha \\ \alpha & \beta & \alpha & \dots & \alpha \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \alpha & \alpha & \alpha & \dots & \beta \end{bmatrix} \\
&= A^T, \ \overrightarrow{\mathrm{b}} = (r, r, ..., r)^T.
\end{aligned} \tag{3.9}
$$

It is known through Definition 1, if $A + A^T$ is positive definite then $A \in S_W$. Therefore, Eq. 3.7 has a non-negative and stable equilibrium point. Based on Eq. 3.9, $A + A^T = 2A$ is a symmetric matrix which is positive definite if only if all its eigenvalues are positive (Theorem 1). Each eigenvalue of $A + A^T = 2A$ can be calculated, and they are:

$$
\begin{aligned}
&\lambda_1 = \alpha(n-1) + \beta, \text{ and} \\
&\lambda_i = \beta - \alpha, \ \forall i \in \{2, ..., n\}.
\end{aligned} \tag{3.10}
$$

Based on Eq. (3.10), if

$$\beta > \alpha > 0, \tag{3.11}$$

all the eigenvalues are positive. Therefore, based on Definition 2 the proposed scheme has a non-negative, stable equilibrium solution when $\beta > \alpha$, i.e. as mentioned in the previous section, the effect of population's size of species to its growth is greater than the effect of another species on population dynamic of its species.

As illustrated in [49], Eq. (3.7) can be expressed to linear complementarity problem (LCP). The solution of LCP can be achieved through solver algorithm such as PATH solver [50–52]. Therefore, through PATH solver, non-negative stable equilibrium solution of the scheme is

$$x_i^* = \frac{K}{\alpha(n-1)+\beta}, \ \forall i \in \{1, 2, 3, ..., n\}. \tag{3.12}$$

Eq. (3.12) is the final steady state transmission rate for each sensor node. Therefore, to avoid buffer overflows, $x_i^* \leq \frac{K}{n}$ bytes. Thus, Eq. (3.12) is satisfied if

$$\alpha(n-1)+\beta \geq n \text{ or } \beta - \alpha \geq n \times (1-\alpha). \tag{3.13}$$

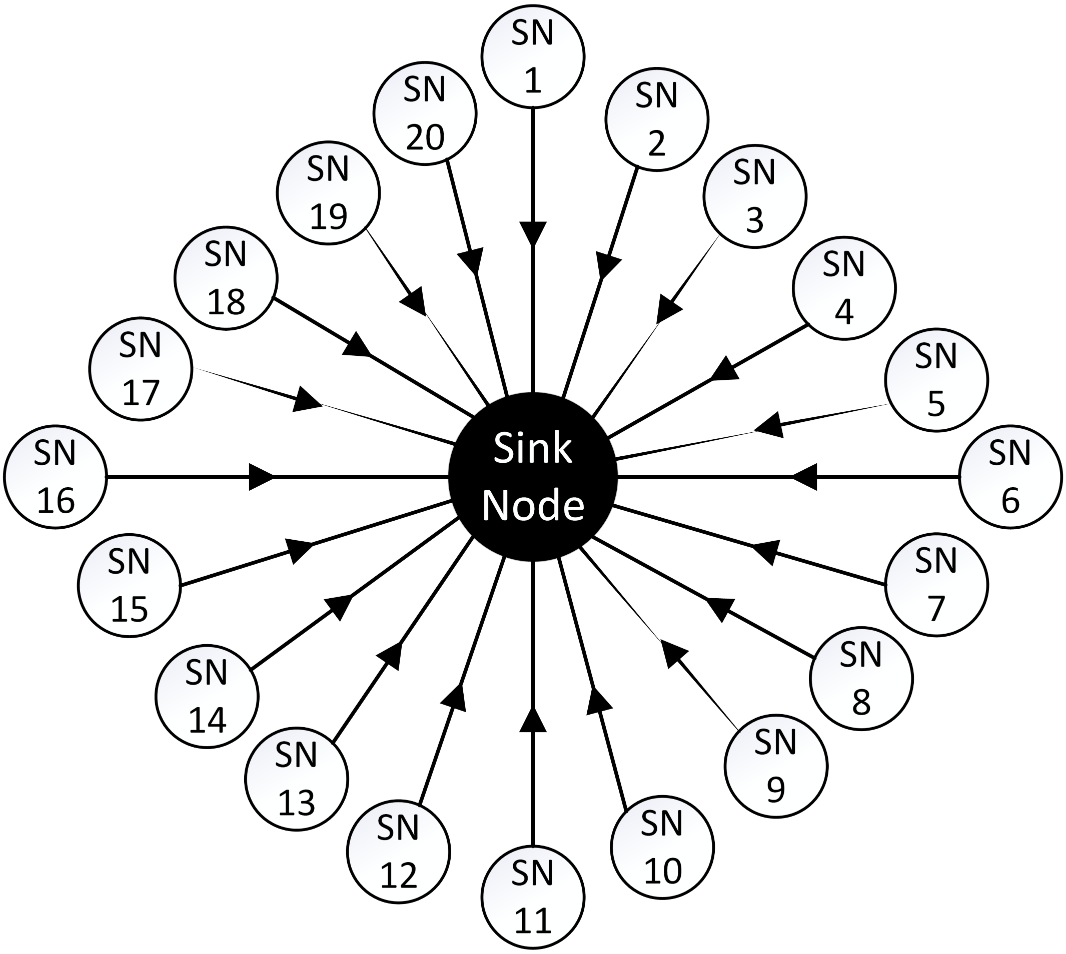


Figure 3.2: Star topology

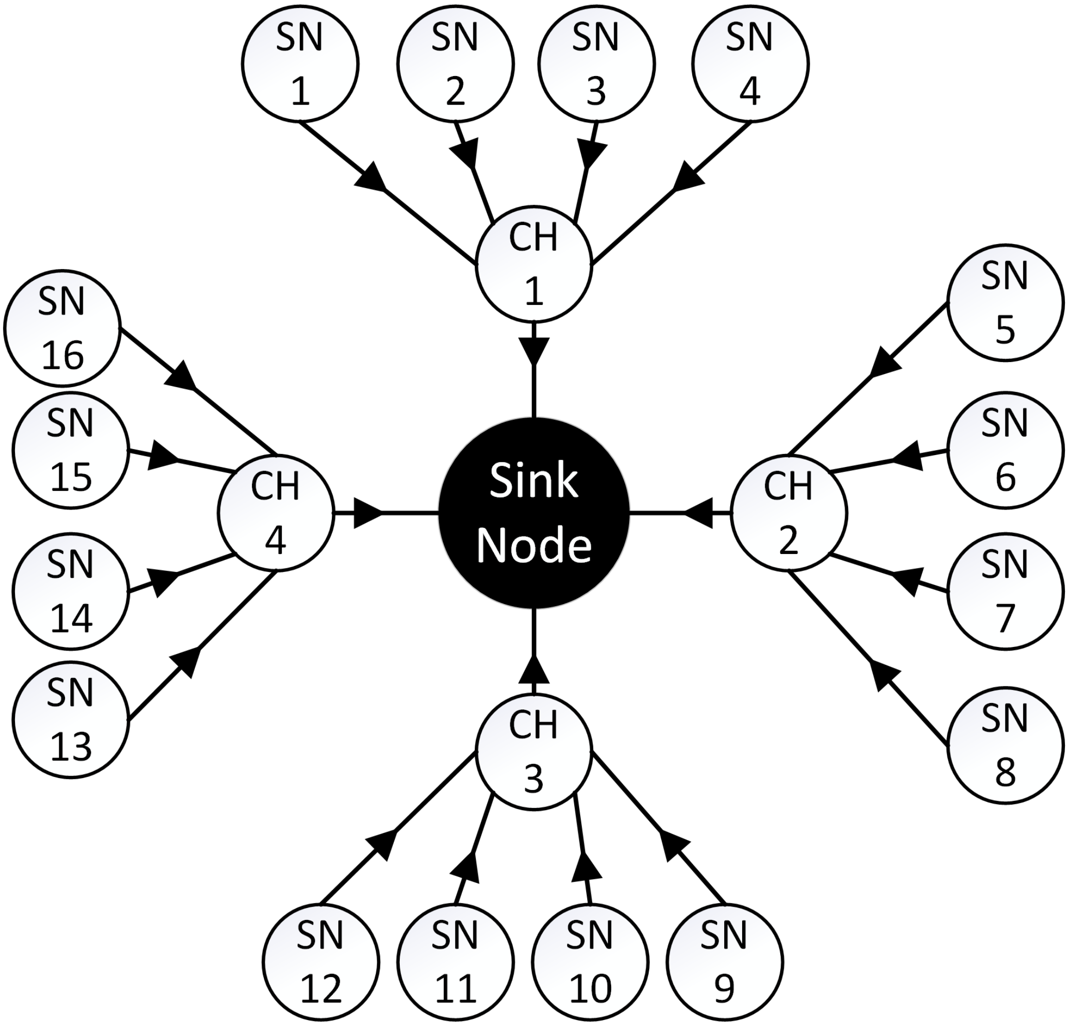


Figure 3.3: Cluster-based topology

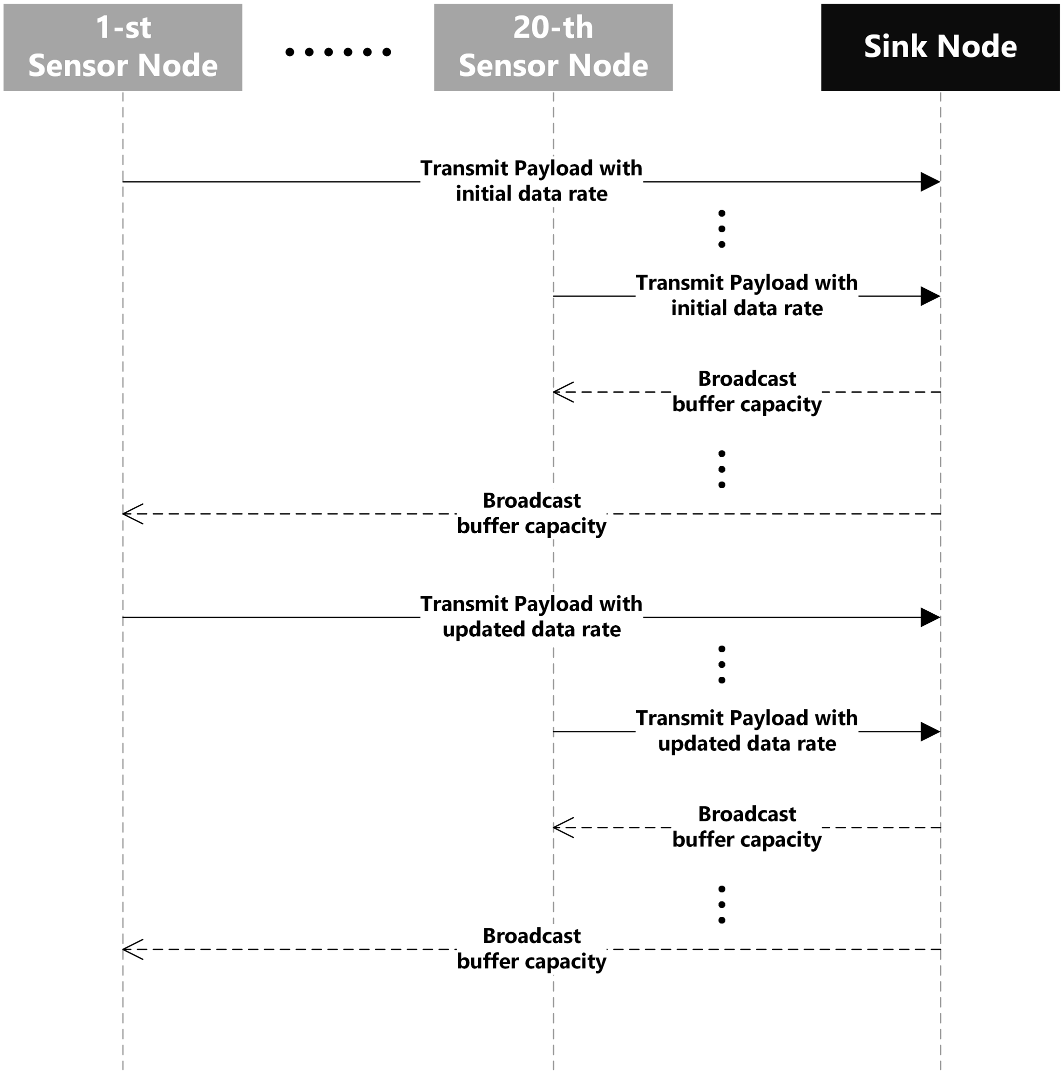


Figure 3.4: Data flow of star topology

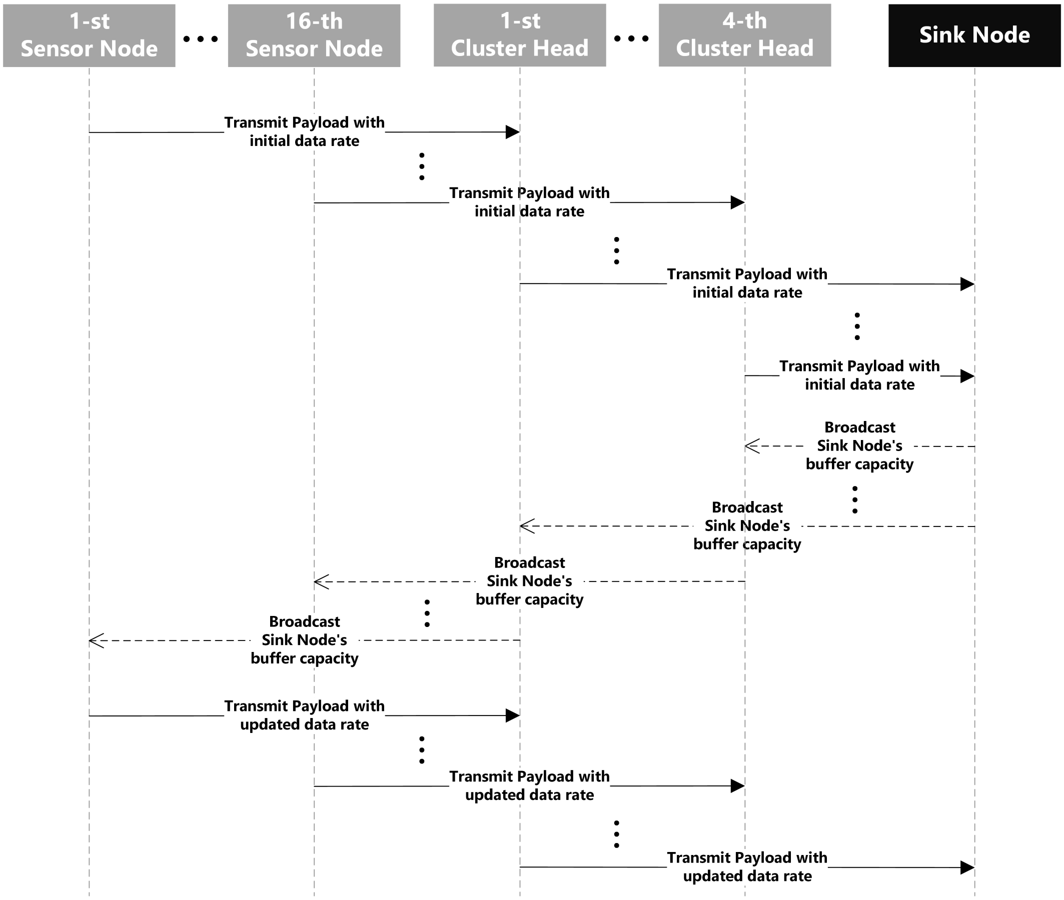


Figure 3.5: Data flow of mesh topology

3.3 Proposed DA for Congestion Control in IIoT

The DA begins by generating a set of random solutions. In each iteration, the velocity and position of each dragonfly are updated using Eq. (2.7) and Eq. (2.8) alternatively, if they do not have neighboring solutions, Eq. (2.9) is used. The algorithm of DA is elaborated in Algorithm 3.1 with $MaxIteration$ as the maximum number of iteration.

In this scheme, DA is used to optimize throughput and minimizing vari-

Algorithm 3.1: DA

Initialize X_i and V_i randomly;
for t **to** $MaxIteration$ **do**
    for $i \leftarrow 1$ **to** N **do**
        if $f(x_i) > X^-$ **then**
            $X^- \leftarrow f(x_i)$;
        else
        end
        if $f(x_i) < X^+$ **then**
            $X^+ \leftarrow f(x_i)$;
        else
        end
        Update V with Eq.(2.7);
        if There is neighboring solutions **then**
            Update X with Eq.(2.8);
        else
            Update X with Eq.(2.9);
        end
    end
end

ance (to maintain fairness) by approaching α and β as input with constraints as expressed in Inequality (3.11) and Inequality (3.13). The objective function $f(\alpha, \beta)$ is calculated in Algorithm 3.2 with M as the number of samples. The penalty method is used to give a penalty if the solution is beyond the constraints with the addition of a huge number.

It must be noted that in DA, each agent should be bounded to minimize searching effort. The lower bound has been already determined by Inequality (3.11). Moreover, the upper bound is set to 10 for simplicity.

Algorithm 3.2: Objective Function

Input : α and β
Output: $f(\alpha, \beta)$

```
sum ← 0;
for t ← 1 to M do
    sum ← sum + 1/X(t);
end
if (β > α) and (β − α ≥ n × (1 − α)) then
    f(α, β) = (sum/M) × VAR(X(t));
else
    f(α, β) = ∞;
end
```

Chapter 4 Performance Evaluation

4.1 Simulation Setup

The proposed scheme was tested in a real network environment using an NS3 network simulator with TSCH model that is developed by European Institute of Innovation & Technology (EIT-ICT) [53,54]. A WSNs consisting of 20 sensor nodes and one sink node with a star topology and mesh topology (4 out of 20 nodes are cluster head in a mesh topology), as shown in Fig.3.2 and Fig. 3.2 were considered. The buffer capacity of each node was set to 30 KB. Moreover, the sampling time was 1 s. The IEEE 802.15.4e TSCH MAC protocol with the two-ray ground radio propagation model is used. Each sensor node transmitted the packet to the sink node with the transmission rate starting from 1 KBps. Every simulation parameter is provided in Table 4.1.

In this thesis, each node can only transmit in one of eighteen levels of data rate. Those data rate are $500, 1500, 2000, 2500, \ldots, 8000$ Kbytes/s. Therefore every second, calculated transmission rate corresponds to the closest available data rate.

Table 4.1: Simulation Parameters

Parameter	Value
MAC layer	IEEE 802.15.4e TSCH
PHY layer	IEEE 802.15.4 PHY
Radio propagation	Two-way gorund
Intial data rate	1 KBps
Packet size	1024 bit
Number of node	20
Buffer capacity	30 KB
Sampling time	1 s
Topology	Star, Mesh
Duty cycle	0.45 and 0.1
Simulation Time	400s
Number of agent	10
$MaxIteration$	5

4.2 Simulation Results

In this scheme, due to the coexistence solution in C-LV model, congestion is always guaranteed. However, the end-to-end delay needs improvement. DA is applied in the C-LV model to minimize the end-to-end delay of each node while transmitting data to the sink node while maintaining fairness and stability. Therefore in this thesis, throughput and stability are considered as the primary metric of this scheme.

As explained before, DA minimizes the end-to-end delay by finding the highest transmission rate possible without any possibility of congestion while maintaining the stability. DA needs only the number of sensor nodes that actively send packets to the sink node. Therefore, if there is a change in the number of active sensor nodes, DA needs to be applied to find closest to the optimal solution of each particular number of sensor nodes. As shown in Fig. 4.1, it takes less than five iterations for the DA find the solution; thus, it does not take any significant time to find the solution.

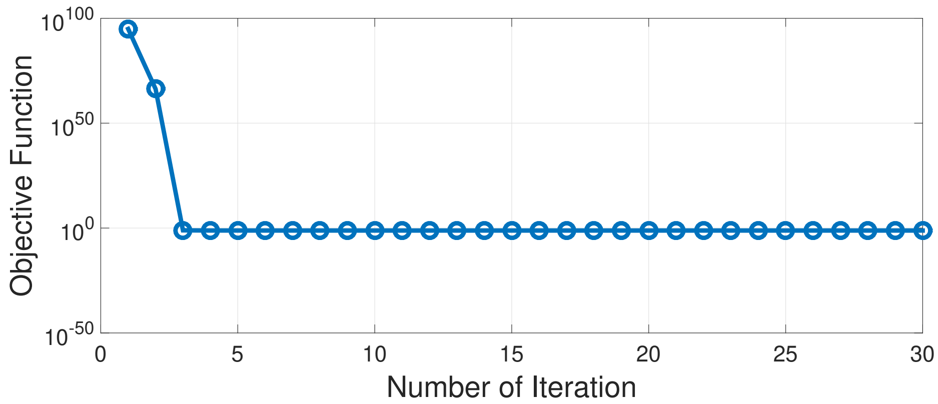


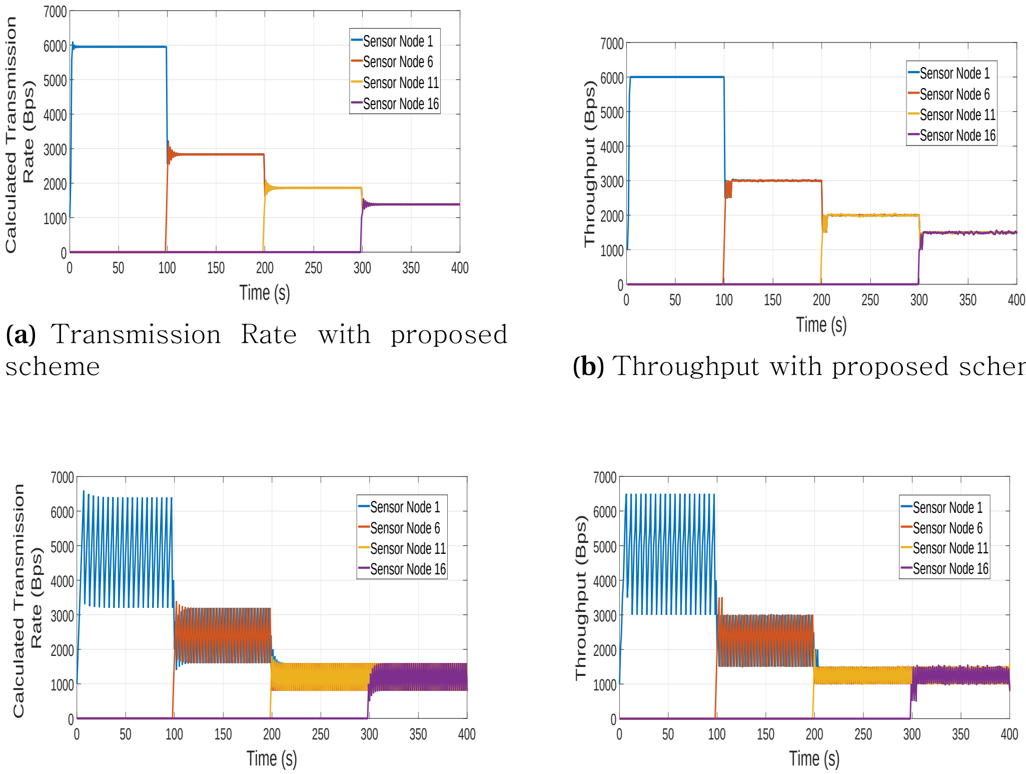
Figure 4.1: Objective Function over Number of Iteration

A particular scenario was considered to evaluate the performance of the proposed algorithms. Two scenarios are investigated. The first scenario was conducted for star topology. At first, there only five active sensor nodes (sensor node 1-5). Every 100 seconds, another five sensor nodes are activated. This scheme continues until all 20 sensor nodes are activated. Through this scenario, the adaptiveness of the hybrid scheme could be assessed. In addition, in this scenario, the proposed scheme is compared with another congestion control Additive increase/multiplicative decrease (AIMD).

For the second scenario, evaluation in mesh topology was conducted. At first, there only four active sensor nodes (sensor node 1-4) which are under cluster head 1. Similar to the first scenario, every 100 seconds, four sensor nodes from another cluster head are activated. This scheme continues until all 16 sensor nodes, and 4 cluster heads are activated. This scenario shows that proposed method can be used for every topology with predefined routing path. In these two scenarios, all sensor nodes have the same priority. However, a scenario with different priority was also conducted.

4.2.1 Simulation Result With Star Topology

The results are shown in Fig. 4.2a and Fig. 4.2b demonstrate that the scheme is adaptive and nearly optimal. Where Fig. 4.2a shows the calculated transmission rate from particular node and Fig. 4.2b shows throughput of particular node measured from the sink node. Even with a harsh industrial environment, recorded throughput showed a similar result with the calculated transmission rate with delay and small noises. As shown in Fig. 4.2b, noise gets stronger as the number of nodes increased due to interference. However, nearly optimal and stable result is shown. The transmission rate is changed rapidly based on the number of sensor nodes. The Proof that this scheme is nearly optimal is shown in Fig. 4.3. In that time, there only 5 active sensor nodes and the buffer capacity is 30 KB. All five sensor nodes transmit nearly 6 KBps without any congestion occurring in the network. Fig. 4.4 shows how fast the scheme adapts when the number of active nodes is increased to 10. When a steady state is achieved, all ten sensor nodes transmit at a rate of nearly 3 KBps. It should be noted that DA works every time there is a change in the number of nodes; thus, this scheme adapts to changing conditions quickly and optimally. To strengthen the proof that DA enhance the C-LV scheme for congestion control, Fig. 4.5 shows the comparative evaluation between C-LV scheme for congestion control with DA (Adaptive) and without DA (Non-Adaptive). When the number of nodes is increased, the calculated transmission rate of non-adaptive C-LV oscillates with high frequency. Moreover, after 300 s, the calculate transmission rate goes extinct because the instability.



(a) Transmission Rate with proposed scheme

(b) Throughput with proposed scheme

(c) Transmission Rate with AIMD

(d) Throughput with AIMD

Figure 4.2: Transmission Rate and throughput in star topology

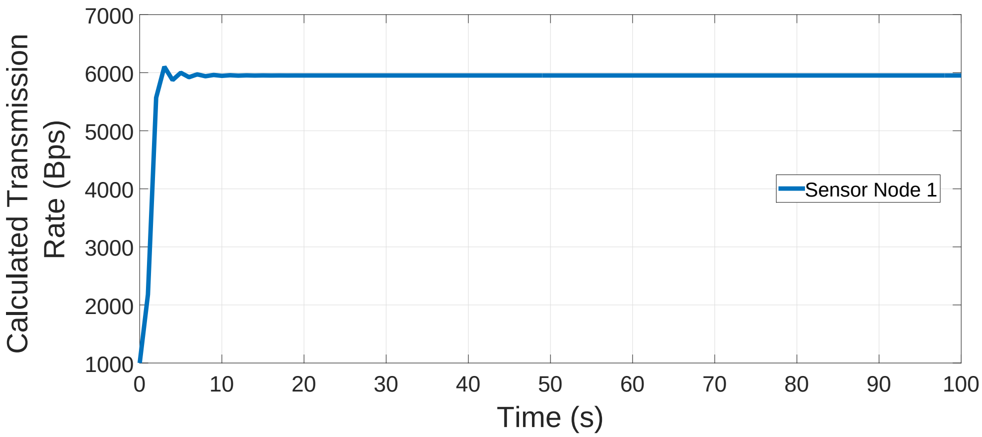


Figure 4.3: Transmission Rate with 5 Nodes Active

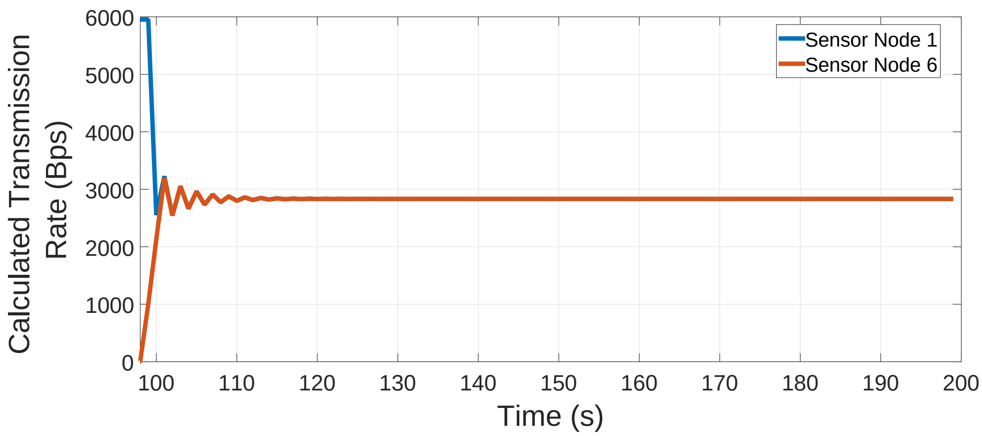


Figure 4.4: Transmission Rate with 10 Nodes Active

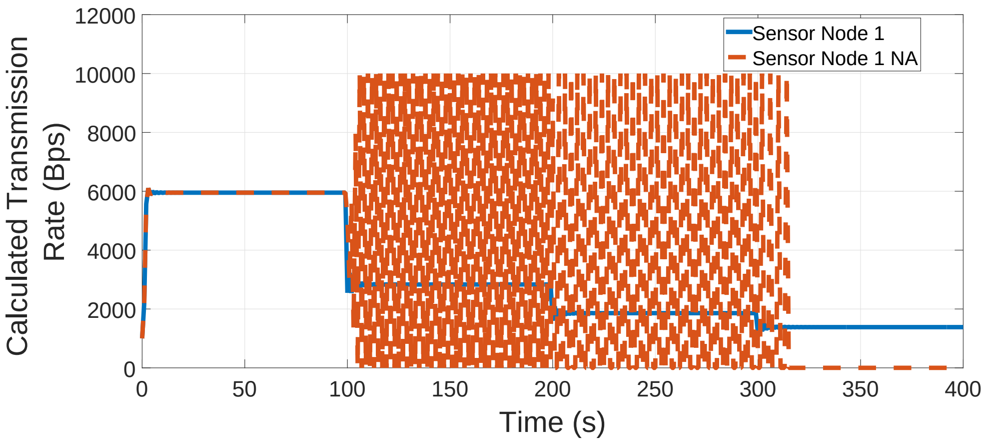


Figure 4.5: Compared with Non-Adaptive Scheme of C-LV

The proposed scheme was compared with conventional AIMD rate adaptation for congestion avoidance. As shown in Fig. 4.2a and Fig. 4.2b, the proposed scheme obtained stable and smooth throughput while maintaining fairness. This smooth result due to calculated transmission rate which fairly determines the value based on available capacity. On the other hand, as shown in Fig. 4.2c and Fig. 4.2d, AIMD scheme shows saw-tooth-like results. This saw-tooth-like result occurs due to multiplicative rate decrease after congestion occurs. Congestion control scheme by AIMD is ineffective in the industrial wireless environment due to harsh condition and frequent packet loss. Furthermore, it leads to high delay and high error rates.

4.2.2 Simulation Result With Mesh Topology

In the second scenario, mesh topology shown in Fig. 3.3 was investigated. In this scenario, the calculated transmission rate from a sensor node to cluster head is determined by Eq. 3.6, and the calculated transmission rate from cluster head to the sink node is determined by Eq. 3.7. As shown in Fig. 4.6, the proposed scheme show a good result. The throughput is still stable when a number of nodes increased even rough noise exists due to interference. This result also shows that this scheme can be scalable and can be applied topology with predefined routing path.

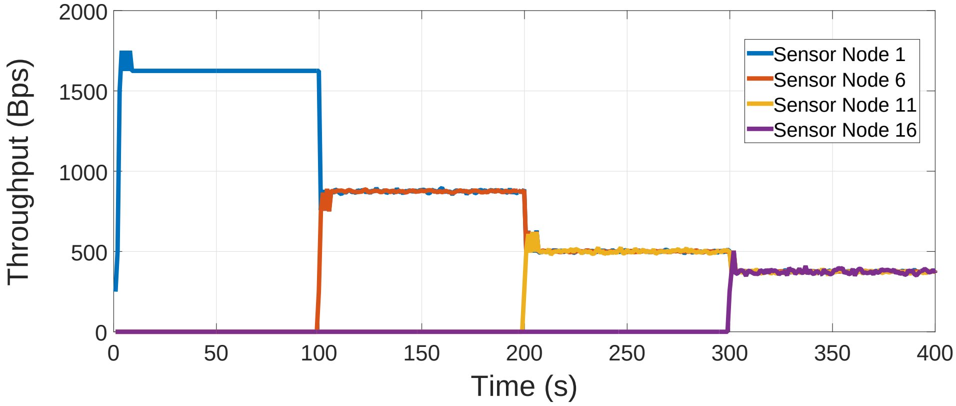


Figure 4.6: Throughput with mesh topology.

4.2.3 Simulation Result With Different Priority

To make different priority classes, α_{ij} has different values for each priority. For instance, in this work, three priority classes were considered. The three priority classes are high, medium, and low. Without loss of generality, it is assumed that $\{1, 2, .., p\} \in \mathbf{H}$, $\{p+1, p+2, .., q\} \in \mathbf{M}$, and $\{q+1, q+2, .., n\} \in \mathbf{L}$, with $p < q < n$. Additionally, **H**, **M**, and **L** are sets of species with high, medium, and low priority class respectively. Therefore, it can be concluded that

$$\begin{aligned} &\forall i \in \mathbf{H},\ a_i = a_H, \\ &\forall i \in \mathbf{M},\ a_i = a_M, \quad \text{with}\ \ a_H > a_M > a_L \\ &\forall i \in \mathbf{L},\ a_i = a_L. \end{aligned} \tag{4.1}$$

In this thesis, evaluation of proposed method with different priority was investigated with star topology. And simulation was conducted with the same scenario that was conducted in star topology section. In this evaluation, $\{SN1, SN6, SN11, SN16\} \in \mathbf{H}$, $\{SN2, SN7, SN12, SN17\} \in \mathbf{M}$, and the rest has low priority. As shown in Fig. 4.7, the proposed scheme works well with different priority. Therefore time-critical data can be prioritized in this proposed scheme.

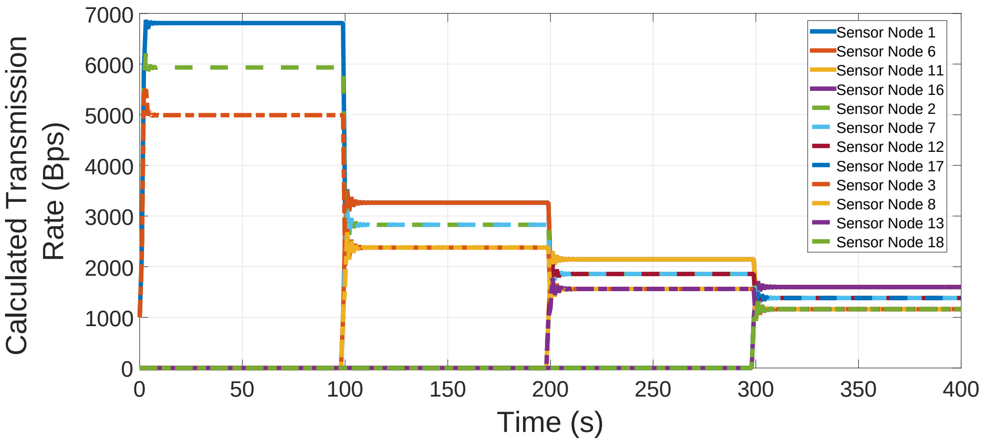


Figure 4.7: Comparing there different priority class

Chapter 5 Conclusions and Future Works

In this thesis, a hybrid bio-inspired algorithm was proposed for congestion control in large-scale IIoT. First, the C-LV model-based scheme is applied to avoid congestion in WSNs and to maintain fairness among sensor nodes. In addition, the DA is applied to enhances the C-LV scheme by optimizing the parameter for minimizing end-to-end delay and to help the system adapt to changes in the number of sensor nodes.

The results verify that this scheme avoids congestion and maintains fairness for each sensor node. Additionally, each sensor node transmits at a nearly optimal rate with any given number of sensor nodes. The DA algorithm enhances the adaptiveness of the system by adapting rapidly. The simulation results show the proposed scheme works with any topology. In addition, this proposed scheme can be modified therefore some node can be prioritized that is critical in IIoT.

From a practical perspective, C-LV does not cost much computational power because it work as network framework. The one that cost mild computational power is DA. However, the cost is paid off with such performance. In addition, the scheme works well because DA adapts to changes rapidly as demonstrated by the results. However, the proposed scheme takes enormous computational power when number of node is greater than thousands. For that case, hybrid between decentralized and centralized network based on Software Defined Network (SDN) and network function visualization (NFV) should be considered.

In future work, the proposed method will be evaluated in a real industrial system. In addition, congestion control with another bio-inspired algorithm will be investigated for comparison.

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