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Priority Based Adaptive Rate Control in Wireless Sensor Networks: A Difference of Differential Approach

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ABSTRACT Wireless Sensor Networks (WSN), when deployed in a real world scenario have to deal with a wide variety of data. Because of the constrained bandwidth, different types of data need to be handled with different priorities in order to prevent congestion in a network. Traffic class priority based rate control algorithms have been proposed by Yaghmaee *et al.* for congestion avoidance and these are based on the rate difference at a given node. In this research work, we have proposed a Difference of Differential Rate Control (DDRC) algorithm at a given node, which is based on the difference of differential rate between sink node and the given node. The next proposed one is Weighted Priority Difference of Differential Rate Control (WPDDRC) algorithm which is based on the combination of the weighted priority of the traffic class and the difference of differential rate of a given node. This is intended to handle Real Time (RT) data, which may be bursty in nature, and also a combination of the RT and Non-Real Time (NRT) data. Though the proposed algorithms are validated on a fixed topology, they are also valid for the general topology of WSN. The proposed algorithms have been implemented in NS3 platform and the performances of the algorithms have been found to be superior to those of counterpart techniques.

INDEX TERMS Rate control, traffic class priority, wireless sensor networks.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have been extensively used in different areas and the challenge encountered is the finite energy with heterogeneous traffic [1], [2]. It is known that the performance of the network depends upon the network topology besides other parameters. Typically, a network topology consists of one or more source and sink nodes together with a large number of sensor nodes distributed over a particular area. The predominant constraints of the WSN are the limited battery energy, bandwidth, processing capability, and finite memory capacity [3].

In the last decade, research works have been focused to develop customized protocols [4] and efficient algorithms to deal with a large volume of data with the availability of a finite bandwidth. It is imperative to transmit data from the source to the sink node with minimal loss. One of the crucial factors of loss of data is the congestion of data in the network and hence circumventing congestion has attracted the attention of many researchers [5], [6]. Overcoming congestion also enhances the lifetime of the nodes.

A wide variety of congestion strategies have been reported in the literature and the rate control is one of those on congestion avoidance. It has been observed that the RT traffic requires low latency and high reliability and therefore needs to be prioritized. In this regard, a priority based rate control algorithm has been proposed by Yaghmaee and Adjeroh [7] to assign different priorities to the RT data and the NRT data. In their work, different rate controls for the sink node, parent node and child node have been proposed taking care of the Global Priorities (GPs) of the nodes. Subsequently, they have applied priority based rate control scheme for health care monitoring [8]. In their research work, the rate control strategy has been proposed considering the traffic class priority and the GP of a node but the queue length of a node has not been taken into consideration. Queue lengths of the nodes

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have been considered by Aghdam *et al.* [9] for their proposed Wireless Multimedia Sensor Networks (WMSN) Congestion Control Protocol (WCCP). The performance of this protocol has been evaluated with different metrics. A priority based routing protocol with service requirements has also been proposed for the congestion control in WSN [10]. Recently, the notion of priority based rate control has been used by Monowar and Bajaber [11] to overcome the congestion and hotspot avoidance in body area networks. The congestion detection is based on the queue occupancy whereas the traffic intensity and the node priority are based on the weighted traffic flows.

An Optimizing Routing algorithm based on Congestion Control (CCOR) has been proposed by Ding *et al.* [12] which is developed based on two functions, namely the link gradient and the traffic radius based on locations. Very recently, the throughput of the WSN has been maximized by a Reliable, Efficient, Fair and Interference-Aware Congestion Control (REFIACC) protocol [13]. This focuses on the fairness of bandwidth utilization among the sensor nodes. The notion of fair allocation of bandwidth among different nodes has also been proposed by Brahma *et al.* [14] to develop rate control strategy, where the congestion control and fair allocation of bandwidth are decoupled.

Limited bandwidth and limited life of the nodes are the constraints which necessitate to judiciously handle the data flow over the network. Hence, transmission of the data over the network without congestion is a technological challenge considering the availability of the limited resources of the network. Therefore, in such situations, it is crucial to design an efficient rate control strategy to simultaneously circumvent congestion and enhance the life period of a node. A sensor network often needs to handle different types of data, particularly the RT data or a mixture of RT and NRT data. The challenge is to handle the RT data together with the the low priority NRT data. The limited resource and the bandwidth of the network would cause network congestion without proper rate control at different nodes. Therefore, a novel rate control strategy needs to be developed while prioritizing the traffic class patterns.

Though priority based rate control algorithms have been proposed in the literature to overcome the congestion due to transmission of the RT data together with the NRT data, circumventing congestion in a network still remains a challenge. The RT data traffic may often be bursty in nature, which when combined with the high priority NRT data makes the problem more compounded. It is to be noted that neither the fair allocation of bandwidth over different nodes nor prioritizing the traffic class suffices to overcome congestion in a network. Hence, in this research work, attempts are made to improve upon the Yaghmaee *et al.*'s algorithm by prioritizing different traffic classes. Yaghmaee *et al.*'s rate control approach is based on the rate difference at a given node, the GPs of a node and the GP of the sink node. But, our proposed rate controls are based on the notion of the difference of the differentials at a given node. The differential corresponds to the change of rate at a given node. The difference of the differentials between a given node and the sink node contributes to the rate control. This difference of differential based rate control is tantamount to the higher order derivative based rate control at a given node. This higher order derivative control is expected to take care of the bursty RT data and the high priority NRT data. Since priority of different traffic classes contribute to the GP of a given node, we have modified the GP with a weighting factor which in turn affects the total priority. Our major contributions are the following,

- Our rate control for any node including the sink node is based on the higher order derivative of the traffic rates i.e. the difference of differential rates across different nodes.
- The global and local priorities are redefined with weighted traffic classes and these new priorities together with the notion of difference of differential rates are used to develop new rate control strategy.

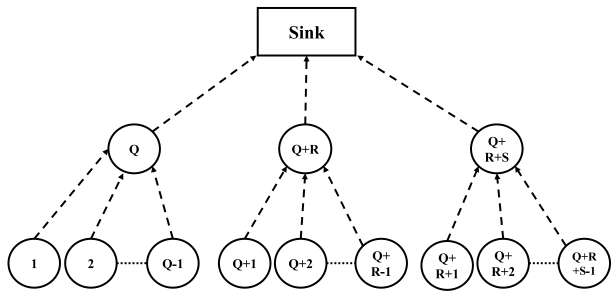

FIGURE 1. General topology.

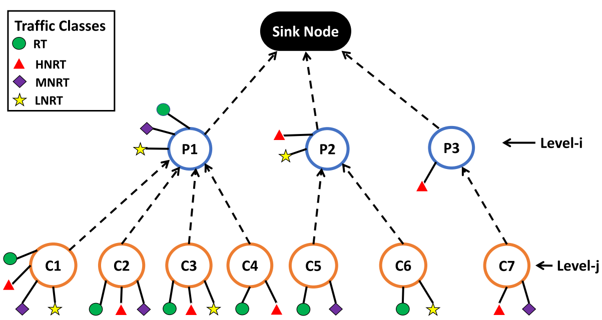

FIGURE 2. A single path network topology.

We have proposed two new algorithms which are based on the priority based rate control strategy. The general network topology is shown in Fig. 1, and for the sake of illustration, we have considered a network topology consisting of one sink node, three parent nodes, and seven child nodes as shown in Fig. 2. It is known that the traffic data rates of the parent nodes depend upon the rates of the connected child nodes. In this work, we have proposed a scheme that controls the traffic rate of each node while taking care of the different priorities of the traffic classes. In the first proposed scheme, the rate of a given node is determined not only by the GP of a given node but also by the difference of differentials between the traffic rate at the sink and a given node. This concept is akin to deal with the higher order derivatives of the data rates resulting from the immediate neighbor nodes and the sink node. The second proposed scheme assigns the total priority that has been modified by making the RT traffic class dominant over the others. This has been achieved by weighting different priorities of the traffic classes connected to different nodes. The modified total priority together with the higher order derivative rate control is the basis of the second algorithm. The proposed algorithms are successfully tested with the above topology in wireless mode and performance is improved as compared to those of Yaghmaee and Adjeroh [7] algorithm, Brahma *et al.*'s [14] algorithm, Monowar and Bajaber [11] algorithm, and Sarode and Bakal [15] algorithm. In addition to throughput, packet loss and packet delay, we have also studied the effect of different traffic class patterns and node mobility on the rate control mechanism. The proposed algorithms have been implemented in NS3 [16] platform in a Linux environment.

This paper is organized as follows. Section 2 provides related work while Section 3 presents the proposed schemes. The two proposed rate control schemes are presented in Section 4. Results and Discussions are provided in Section 5 when the concluding remarks are presented in Section 6.

II. RELATED WORKS

From the early days of research in the area of WSN, congestion has been an issue to cause loss of data during transmission. Therefore, congestion detection and avoidance have been the research focus for more than three decades. To mitigate the effects of congestion, different algorithms and schemes have been proposed in the early nineties of the last century [17]–[19]. Floyd and Jacobson [19] proposed early detection scheme without considering the TCP delays which has been taken care by Wan *et al.* [20] while proposing the Congestion Detection and Avoidance (CODA) scheme. The issue of MAC layer protocol has been taken care by Hull *et al.* [21], where the authors have prioritized the MAC protocol and fused this with the protocols for flow control and rate limiting source traffic. These combined protocols enhanced the performance by three times under realistic workloads. This implied that fusion of different protocols is one of the means of overcoming congestion in the network. In a real world scenario, many sensors transmit data to the base station thus creating a situation of many-to-one multi hop routing, where there could be congestion in the nodes close to the base station. Ee and Bajcsy [22] have addressed this issue by proposing an algorithm in the transport layer and their algorithm is designed to work with any MAC protocol. Sensor Transmission Control Protocol (STCP), a transport layer protocol has also been proposed by Iyer *et al.* [23] to overcome the congestion. Their algorithm has been implemented at the sink node to control the flow type, reliability, and throughput of each node. Unlike the previous algorithm, the authors have not designed the algorithm to work with any MAC protocol. In order to further enhance the potentiality of the congestion avoidance algorithm, the notion of cross layer optimization has been used by Wang *et al.* [24] to develop a Priority based Congestion Control Protocol (PCCP). This algorithm takes care of the node priority index, the degree of congestion, and overcomes both node level and link level congestion.

In the literature, the notion of priority has been extended to the traffic class as well. Yaghmaee and Adjeroh [7] have prioritized the traffic class and defined the GP at each node. They have also used the above notion for monitoring health of patients in real time environment [8]. Their proposed protocol improved the QoS but failed to solve the hotspot problem of the network due to high rate of data transmission. This issue has been addressed recently by Monowar and Bajaber [11], who have proposed a rate control mechanism for implantable Wireless Body Area Network (WBAN) to overcome the congestion and hotspot avoidance. They have controlled the congestion based upon queue occupancy and traffic intensity of the body sensor network. The notion of priority has also been applied to packet transmission and hop-by-hop flow control by Sumathi and Srinivasan [25].

The problem of transmission of the prioritized nodes in a long range WSN has been addressed by Sarode and Bakal [15], who have proposed three algorithms to overcome congestion. The proposed algorithms did not consider the queuing model at the node level of the network. But, congestion avoidance based on queue management has been dealt by Rezaee *et al.* [26] while using WSN for health care. They have proposed Active Queue Management (AQM) based protocol for stationary patients, but in their subsequent work they have developed a Health-care aware Optimized Congestion Avoidance and control protocol (HOCA) [27] to avoid congestion during transmission of critical patients. The traffic class priority has also been used by Swain and Nanda [28] to propose an adaptive rate control algorithm to overcome congestion in WSN. The proposed algorithm is developed using the notion of the difference of differentials. In the traffic class priority strategy, by and large, RT traffic is given high priority. But Tshiningayamwe *et al.* [10] have proposed a priority based routing protocol to differentiate the service requirements by mixing a RT traffic with three NRT traffic. Besides the notion of priority, transmission of critical patient data in real time environment has been dealt by Yaakob and Khalil [29], where they have attempted to overcome congestion by combining notions of Relaxation Theory and Max-Min fairness.

In addition to the notion of priority, the notion of load balancing and fair allocation of bandwidth have been used to overcome congestion. Brahma *et al.* [14] have proposed a protocol which is based on Fairness Rate Control (FRC) to achieve the fair allocation of bandwidth. In their work, they have addressed the problem by decoupling the fair allocation of bandwidth and the congestion control. The notion of load balancing is employed by Chughtai *et al.* [30] where the network congestion has been overcome by discovering a node route based on a composite metric. Additionally, Tan and Kim [31] have proposed a distributed traffic-balancing routing algorithm based on gradient index of each node. This indexing could achieve the traffic balancing from sources to sinks. Using the gradient search method, they have simultaneously balanced the optimal paths and overcome the congestion in the network with a view to achieve low packet delay, low energy consumption, and high packet delivery ratio. In the sequel, a Grid-based Multi-path with Congestion Avoidance Routing (GMCAR) protocol has been proposed by Banimelhem and Khasawneh [32]. In this scheme, grid densities together with the hop count of different grids have been used to take routing decisions with a view to control the congestion in the gridded sensor networks. A Secure Selective Dropping Congestion Control (S^2DCC) mechanism has been proposed by Tortelli *et al.* [33] to improve the image quality at the sink node by adopting different strategies such as end-to-end ciphering, hierarchical and hybrid network design, in-network selective data dropping, and scalable multimedia encoding. Recently, nature inspired computing algorithms such as cuckoo search [34], particle swarm [35] algorithms, Imperialistic Competitive Algorithm (ICA) [36] have been employed for optimizing the rate adjustment at the child node and the parent node for congestion avoidance. In order to maintain the high data accuracy in a cyber physical system, the issue of congestion has been resolved by Zhuang *et al.* [37] with their proposed Congestion-Adaptive Data Collection scheme (CADC). Their algorithm has overcome congestion by adhering the notion of lossy compression.

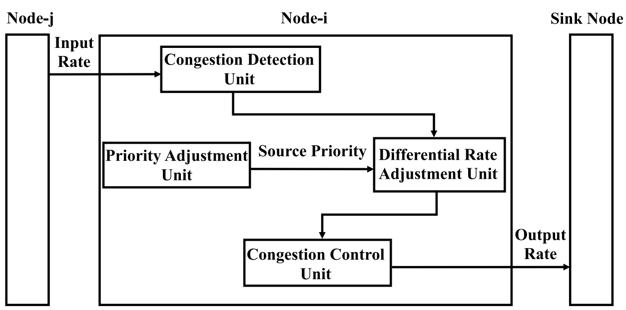

FIGURE 3. Schematic representation of the proposed congestion free model.

III. PROPOSED SCHEMES

For effective use of the bandwidth and reducing the loss of data due to congestion, we intend to design a rate control mechanism for overcoming congestion in the network. In this regard, Fig. 3 and Fig. 4 are the schematic representations of the proposed schemes, where Fig. 3 corresponds to congestion free situation while Fig. 4 corresponds to the congestion avoidance case. In this mechanism, our novelty is the addition of the Differential Rate Adjustment Unit (DRAU) and Priority Adjustment Unit (PAU). The DRAU computes the difference of differentials at a given node. Our PAU is different from Yaghmaee *et al.*'s in the sense that it computes the weighted priority P_w at a given node. As observed from Fig. 3 and Fig. 4, a j^{th} node is connected to i^{th} node which in turn is connected to the sink node. The i^{th} node has been provided with the rate control mechanism to avoid the congestion. As observed from Fig. 3, when there is no congestion, the input rate and output rate of the i^{th} node are not required to be controlled. But in case of congestion, the i^{th} node will be notified with the congestion situation by the sink node and will control the input rate by providing the updated rate for the j^{th} node, which is shown in Fig. 4. In this case, the different internal units of the i^{th} node become active and contribute. In Fig. 4, the Congestion Detection Unit (CDU) and the PAU feed to the DRAU. The function of the CDU is to detect the congestion by calculating the difference of the input rate and the output transmission rate at each node, which can be a positive value or a negative value. Thereafter, it forwards the difference value to the DRAU. We have considered the general topology as shown in Fig. 1, which is the same as that of Yaghmaee and Adjeroh [7]. The general topology has a sink node but the intermediate nodes are denoted by Q^{th}, $(Q+R)^{th}$, and $(Q+R+S)^{th}$ node. These nodes are designated as parent nodes. The next layer of connected nodes is shown as 1, 2, .., $(Q+R+S-1)$ node. We have developed our algorithms for this general topology. For the sake of illustration, we have considered a topology with $Q = 5, R = 3$ and $S = 2$. This has resulted in the specific topology with eleven nodes as shown in Fig. 2. The intermediate nodes are designated as the parent nodes. Therefore, we have tested our algorithms on this topology and hence algorithms will be valid for the general topology of Fig. 1 as well. In the single path tree topology as shown in Fig. 2, we have considered different traffic classes such as RT and NRT data and have assigned the priority to these traffic classes to overcome the congestion in the network. In this regard, a new unit, PAU has been added and the function of this new unit is to assign different priority levels to different classes. The functionality of the DRAU is based on the concept of difference of differentials computed at a given node. This unit also controls the rate at each node with a view to enhance the throughput without an occurrence of the congestion in the network. This notion introduces the higher order derivative control at the sink node and other intermediate nodes. This helps to smoothen the high data rate or burst data rate at a node thereby avoiding congestion in the respective nodes. The Congestion Control Unit (CCU) is responsible for notifying all the child nodes

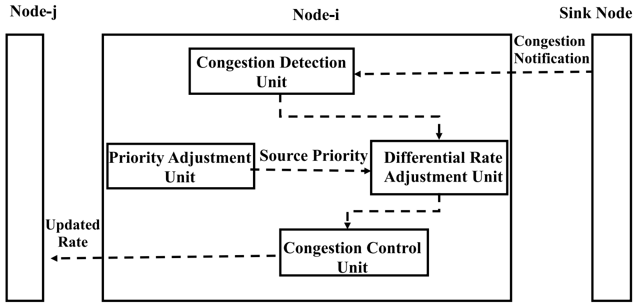

FIGURE 4. Schematic representation of the proposed congestion control model.

with the new updated rate. When any node detects any congestion, the CCU adjusts the transmission rate accordingly.

A. PRIORITY BASED RATE CONTROL

In a real world scenario, analysis of a given situation requires to have multiple data gathered from the same event. In such situations, typically WMSN are employed. In this WMSN, a variety of data are usually collected by different sensors connected to the sensor nodes [3]. These data types could be gathered by different sensors such as audio, video, and scalar. These collected data have inherently different priorities and hence demand different service architectures. The data traffic broadly can be categorized as RT and NRT. The Delay and jitter are the crucial attributes of the RT traffic and if uncontrolled, these may lead to congestion in the network. The congestion problem can be circumvented by adopting appropriate rate control mechanism. Usually, the nature of the RT data is bursty and hence demands different priority level as compared to the NRT data. The above arguments justify the necessity of priority assignment for both the RT and the NRT data.

In our work, it has been intended to consider different types of NRT data and specifically, we have considered three types of data. They are: (I) High priority NRT (HNRT) data, (II) Medium priority NRT (MNRT) data, and (III) Low priority NRT (LNRT) data. Each of these data set has been assigned with a particular priority level. The NRT data are classified based on the data rate and we categorized the rates as high, medium, and low. These are identified by the data rates within different ranges. The nodes will also identify based on the rates within the prespecified range.

Fig. 2 shows the network topology considered in this research work. In this topology, different traffic classes have been assigned to each node. Out of the 11 nodes, one sink node, P1, P2 and P3 are the parent nodes while C1, C2, C3, C4, C5, C6 and C7 are the child nodes. The nodes C1, C2, C3, C4, C7, P2 and P3 have been assigned with the HNRT class, the nodes C1, C2, C5, C7 and P1 have been assigned with the MNRT class, the nodes C1, C3, C6, P1 and P2 have been assigned with the LNRT class and the nodes C1, C2, C3, C4, C5, C6 and P1 have been assigned with the RT class respectively.

IV. PROPOSED RATE CONTROL SCHEMES

It is known that the WSN nodes gather both the RT and the NRT data when deployed in a real world environment. The RT data may be bursty in nature. Some of the NRT data may have high data rate. Therefore, assigning proper priority to the traffic class is a pivotal issue for congestion avoidance. Besides, to deal with the bursty RT data, we have developed this notion of higher order derivative that contributes while determining the rate at a given node. This is computed as the difference of differentials with respect to the sink node. This corresponding additional term in the rate update equation is one of the factors for improvement. Besides, we have weighted the priorities of different traffic classes and obtained the new weighted traffic class priorities. The combination of this weighted traffic class together with the higher order derivative terms account for the improvement of our results. Since different data types with different priority levels need to be processed, an efficient rate control scheme is necessary to prevent congestion and hence data loss over the network. The following are some of the terms defined to be used to formulate the strategy and thereafter develop the algorithm. In this research work, two novel strategies have been proposed which resulted in two new algorithms of the rate control at different nodes. These two proposed schemes can be viewed as the modification to the scheme proposed by Yaghmaee and Adjeroh [7]. Let, P^i_{TC} denotes the traffic class priority and P^i_{GE} denotes the geographical priority of i^{th} node respectively. Let SP^i_m denotes the traffic source priority of i^{th} sensor node, where m denotes the set of traffic classes, and $m \in \{RT, HNRT, MNRT, LNRT\}$. In i^{th} node, the value of P^i_{TC} is the sum of individual source priorities and is given by,

$$P^i_{TC} = \sum_m SP^i_m. \tag{1}$$

The total priority of the i^{th}node, P^i is defined as follows,

$$P^i = P^i_{TC} \cdot P^i_{GE}. \tag{2}$$

The traffic class priority (P^j_{TC}) of the j^{th} child nodes has been computed as,

$$P^j_{TC} = \sum_m SP^j_m. \tag{3}$$

where, SP^j_m is the source priority of j^{th} child nodes. The total priority (P^j) of the j^{th} child node is,

$$P^j = P^j_{TC} \cdot P^j_{GE}. \tag{4}$$

where, P^j_{GE} is the geographical priority of the j^{th} child node. The GP at the j^{th} child node (GP^j) has been computed as,

$$GP^j = P^j. \tag{5}$$

If $C(i)$ be the set of the child nodes of i^{th} node, then the i^{th} node GP is calculated as,

$$GP^i = \sum_{j \in C(i)} GP^j + P^i. \tag{6}$$

In the following, we explain the proposed Difference of Differential Rate Control (DDRC) and Weighted Priority Difference of Differential Rate Control (WPDDRC) strategies for congestion avoidance.

A. DDRC BASED RATE CONTROL STRATEGY

In the topology considered, the flow of data is from the child node to the sink node via the parent node. These parent nodes serve as the child nodes of the sink node. The congestion needs to be avoided depending upon the rate of the sink node. Let the rate of change at the sink node and i^{th} node be denoted as Δr^{Sink} and Δr^i respectively, which are same as defined in our previous work [28].

It is intuitively appealing that the difference of the rate of change of the sink and a given node should contribute to the congestion avoidance. In other words, this difference of differentials serves as the higher order derivative of the rate at a given node. These higher order differentials have been weighted by a weighting parameter μ, thus $\mu\left(\Delta r^{sink} - \Delta r^i\right)$ will be able to contribute towards the rate control at a given node of the network. In order to compute the rate control, initially different priorities such as traffic class priority P^i_{TC}, individual node priority P^i and the Global Priority GP^i of a node are computed using (1), (2) and (6) respectively.

In order to compute the higher order derivative, the difference of input and output rates at the sink node is computed. The output rate of the sink node is inversely proportional to the average service time of a packet at the sink; $r^{Sink}_{out} \propto \frac{1}{\overline{T}^{Sink}_s}$, where r^{Sink}_{out} is the output rate of the sink, $\overline{T}^{Sink}_s$ is the average service time of the sink node. Exponentially Weighted Sum has been used to compute the average service time $\overline{T}^{Sink}_s$, which is expressed as,

$$\overline{T}^{Sink}_s(n+1) = (1-\alpha)\overline{T}^{Sink}_s(n) + \alpha \cdot T^{Sink}_s. \quad (7)$$

where, α is a positive constant between 0 and 1.

As observed from the topology, the parent nodes are connected to the sink node and therefore are regarded as the child nodes of the sink. The transmission rate of the i^{th} connected parent node is r^i_{out}, which can be determined based on the GPs. The rates of this i^{th} node and the sink node are proportional to their GPs. Assuming the proportionality constant to be unity, the maximum rate of the i^{th} parent node is,

$$r^i_{out} = r^{Sink}_{out} \cdot \frac{GP^i}{GP^{Sink}}. \quad (8)$$

where, GP^{Sink} is the GP of the sink node and is determined as $GP^{Sink} = \sum_{i\in C(Sink)} GP^i$, which is the sum of the GPs of the connected child nodes of the sink. These child nodes of the sink are the parent nodes in our topology shown in Fig. 2. Since the output rate of the connected child nodes will contribute to the input rate of the sink node, the input rate of the sink node is given as $r^{Sink}_{in} = \sum_{i\in C(Sink)} r^i_{out}$, where r^i_{out} corresponds to the output rate of each child node. Hence, the rate difference at the sink node Δr^{Sink} is expressed as,

$$\Delta r^{Sink} = \beta \cdot r^{Sink}_{out} - r^{Sink}_{in}. \quad (9)$$

where, β is a positive constant between 0 and 1.

Based on the above, the new update rate propagated by the sink node towards the child nodes i.e. the parent nodes of the topology is given by,

$$r^i_{out} = r^i_{out} + \Delta r^{Sink} \cdot \frac{GP^i}{GP^{Sink}}. \quad (10)$$

where, r^i_{out} is the output rate of the i^{th} connected child node of the sink.

The input rates of the parent nodes will be the sum of the output rates of the connected child nodes. Therefore, the input rate of the i^{th} parent node is $r^i_{in} = \sum_{j\in C(i)} r^j_{out}$, where $C(i)$ is the set of the child nodes connected to the i^{th} parent node. The rate difference Δr^i of the i^{th} parent node is given by,

$$\Delta r^i = \beta \cdot r^i_{out} - r^i_{in}. \quad (11)$$

where, β is a positive constant between 0 and 1.

Considering the higher order derivatives, the proposed output rate of the j^{th} child node is given by,

$$r^j_{out} = r^j_{out} + \Delta r^i \frac{GP^j}{GP^i} + \mu[(\Delta r^{Sink} - \Delta r^i)\frac{GP^j}{GP^i}]. \quad (12)$$

The child nodes will be constrained to this new updated rate to avoid congestion. The flowchart for the DDRC algorithm is presented in Fig. 5. In this case, the update rate of the parent and the child nodes are computed by (12).

Salient steps of the Algorithm are enumerated below.

1) DDRC ALGORITHM

Step 1: Initialize the parameters such as service time (T^{Sink}_s), β, γ, μ, and the traffic class priorities.

Step 2: Evaluate the average service time using (7),

$$\overline{T}^{Sink}_s(n+1) = (1-\alpha)\overline{T}^{Sink}_s(n) + \alpha \cdot T^{Sink}_s.$$

Step 3: Compute the rate difference at the sink node and i^{th} parent node by evaluating (9) and (11),

$$\Delta r^{Sink} = \beta \cdot r^{Sink}_{out} - r^{Sink}_{in},$$
$$\Delta r^i = \beta \cdot r^i_{out} - r^i_{in}.$$

Step 4: Compute the updated output rate of the i^{th} parent node by evaluating (10),

$$r^i_{out} = r^i_{out} + \Delta r^{Sink} \cdot \frac{GP^i}{GP^{Sink}}.$$

Step 5: Compute the updated rate of the i^{th} parent node propagated to the j^{th} child node using (12),

$$r^j_{out} = r^j_{out} + \Delta r^i \frac{GP^j}{GP^i} + \mu[(\Delta r^{Sink} - \Delta r^i)\frac{GP^j}{GP^i}].$$

Step 6: Repeat steps 2 to 5 till completion of the specified simulation time.

B. WPDDRC BASED RATE CONTROL STRATEGY

The above proposed DDRC algorithm is based on the higher order derivative based rate control and this will overcome congestion in the network. In order to improve the rate control, the priority assignment of the traffic classes may be modified besides the higher order derivative based rate control. This higher order derivative based algorithm is expected to control the bursty RT data. This notion is further reinforced by assigning a high priority to the RT traffic and simultaneously reducing the priority for NRT data. Thus, the total priority at a given node has been controlled. This controlled priority contributes to achieve the desired rate control for congestion avoidance.

Initially, the traffic class priority of the i^{th} node may be computed as,

$$P^i_{TC} = \sum_m SP^i_m.$$

Since, there are RT and NRT traffic classes, the RT traffic class is expected to play a dominant role in the total priority and hence, we have assigned the highest priority to RT. Besides, the total traffic class priority contributing the total priority of the i^{th} node is reduced by the weighted sum of the NRT traffic class. Hence, the proposed weighted total priority for i^{th} node (P^i_w) is expressed as,

$$P^i_w = P^i_{TC} \cdot P^i_{GE} + [W_{RT} - \gamma(W_{HNRT} + W_{MNRT} + W_{LNRT})]. \quad (13)$$

where, γ is a positive constant, $0 \leq \gamma \leq 1$ and W_{HNRT}, W_{MNRT}, W_{LNRT}, W_{RT} are the weights assigned to the RT and the NRT traffic classes. The traffic class priority (P^j_{TC}) of the j^{th} child node has been computed as,

$$P^j_{TC} = \sum_m SP^j_m. \quad (14)$$

where, SP^j_m is the source priority of the j^{th} child nodes. The proposed weighted total priority (P^j_w) of the j^{th} child node is,

$$P^j_w = P^j_{TC} \cdot P^j_{GE} + [W_{RT} - \gamma \cdot (W_{HNRT} + W_{MNRT} + W_{LNRT})]. \quad (15)$$

where, γ is a positive constant, $0 < \gamma \leq 1$ and P^j_{GE} is the geographical priority of the j^{th} child node. The weighted GP of the j^{th} child node (GP^j_w) changes to $GP^j_w = P^j_w$. The weighted GP at the i^{th} parent node (GP^i_w) changes to,

$$GP^i_w = \sum_{j \in C(i)} GP^j_w + P^i_w. \quad (16)$$

The maximum output rate of the i^{th} parent node using above weighted priority can be evaluated as,

$$r^i_{out} = r^{Sink}_{out} \cdot \frac{GP^i_w}{GP^{Sink}_w}. \quad (17)$$

where, GP^{Sink}_w is the weighted GP of the sink node and is determined as $GP^{Sink}_w = \sum_{i \in C(Sink)} GP^i_w$, which is the sum of the weighted GP of the connected child nodes of the sink. With the modified GP of (16) and output rate of (17), the updated rates of the sink node and the parent nodes are computed analogous to (9),(10) and (11). They are expressed as follows,

$$\begin{aligned} \Delta r^{Sink} &= \beta \cdot r^{Sink}_{out} - r^{Sink}_{in}, \\ r^i_{out} &= r^i_{out} + \Delta r^{Sink} \cdot \frac{GP^i_w}{GP^{Sink}_w}, \\ \Delta r^i &= \beta \cdot r^i_{out} - r^i_{in}. \end{aligned} \quad (18)$$

The proposed updated rate is defined by,

$$r^j_{out} = r^j_{out} + \Delta r^i \frac{GP^j_w}{GP^i_w} + \mu[(\Delta r^{Sink} - \Delta r^i)\frac{GP^j_w}{GP^i_w}]. \quad (19)$$

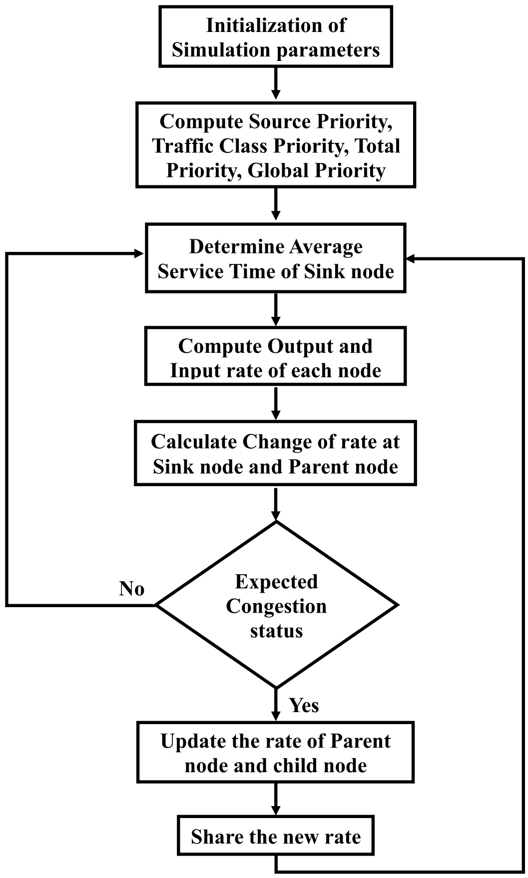

FIGURE 5. Flowchart of proposed DDRC and WPDDRC algorithms.

This updated rate is propagated to the child node by its respective parent node. The flowchart presented in Fig. 5 is also valid for WPDDRC algorithm. In this case, the update rates of the parent and the child nodes are achieved by (19).

1) WPDDRC ALGORITHM

Salient steps of WPDDRC algorithm are same as DDRC algorithm with the proposed modified total priority presented in (13) and are as follows

Step 1: Initialize the parameters such as service time (T^{Sink}_s), β, γ, μ, and the traffic class priorities.

Step 2: Evaluate the average service time using (7),

$$\overline{T}^{Sink}_s(n+1) = (1-\alpha)\overline{T}^{Sink}_s(n) + \alpha \cdot T^{Sink}_s.$$

Step 3: Compute the rate difference at the sink node and the i^{th} parent node by evaluating (9) and (11),

$$\begin{aligned} \Delta r^{Sink} &= \beta \cdot r^{Sink}_{out} - r^{Sink}_{in}, \\ \Delta r^i &= \beta \cdot r^i_{out} - r^i_{in}. \end{aligned}$$

Step 4: Compute the updated output rate of the i^{th} parent node by evaluating (18),

$$r^i_{out} = r^i_{out} + \Delta r^{Sink} \cdot \frac{GP^i_w}{GP^{Sink}_w}.$$

Step 5: Compute the updated rate of the i^{th} parent node propagated to the j^{th} child node using (19),

$$r_{out}^{j} = r_{out}^{j} + \Delta r^{i}\frac{GP_w^j}{GP_w^i} + \mu[(\Delta r^{Sink} - \Delta r^{i})\frac{GP_w^j}{GP_w^i}].$$

Step 6: Repeat steps 2 to 5 till completion of the specified simulation time.

Hence, in the first algorithm the last term in (12) is the difference of differential which is our contribution. In the second algorithm, one of our contributions is the weighted GP as presented in (13) and (15). Besides, our novelty in the computation of rate is the weighted GP together with the difference of differential as provided in (19). The difference of differential is the last term of (19).

TABLE 1. Simulation parameters.

Parameter	Values
Simulation area	$100 * 100\ m^2$
MAC layer	IEEE 802.11
Number of sensor nodes	11
Packet size	172 Bytes
Data rate	2 Mbps
Tx power	281.84 mW
Operating frequency	5 GHz
Traffic source	CBR
Routing protocol	AODV
Mobility model	Random Walk2d mobility Model
Node C1, C3 mobility	10 m/s
Pause time	No pause time
Simulation time	100 Seconds

V. EXPERIMENTS AND DISCUSSIONS

For the sake of illustration, we have considered a specific network topology of the general network topology [7] as shown in Fig. 2. Though our algorithms have been validated over a network of eleven sensor nodes distributed over $100 * 100\ m^2$ grid, the algorithms are also valid for the general topology. The proposed algorithms with the above topology have been implemented using the network simulator NS3 in Linux environment. Each node is connected to different classes of data traffic as shown in Fig. 2, while the communications among the nodes are established based on AODV routing protocol. The service time for the sink node is fixed at 1 ms. The average service time of the sink node is based upon the service time of the sink node, as given by (7). Therefore, the time for the sink node to compute the rate and respond to the node will be within the service time of the node. In order to assign high priority to the RT data and a gradual decrease of priority to different NRT data, we have assigned a priority of 10 to RT and 6, 3, 1 to HNRT, MNRT, and LNRT data respectively. The other parameters considered in simulation are presented in Table 1. The values of β, γ, and μ of the two proposed algorithms were tuned to be optimized at 1, 0.5, and 0.9 respectively.

As observed from Fig. 2, the three parent nodes P1, P2, and P3 are connected to a different set of the child nodes. For example, P1 is connected to four child nodes and hence the rate of the parent node depends on the rates of the child nodes. For performance comparison, we have considered throughput, packet loss, and packet delay of a given node. Although we have computed the above three parameters for all the nodes, we have presented the parameters only for the two child nodes such as C1 and C3 and the parent node P1. We have chosen P1 because of the fact that this node is connected to four nodes with all types of the traffic classes. The child node C1 is selected because it is connected to all types of the traffic classes including the RT traffic class. Out of rest of the child nodes, C3 is selected as it has the RT traffic class and the highest and the lowest NRT traffic classes.

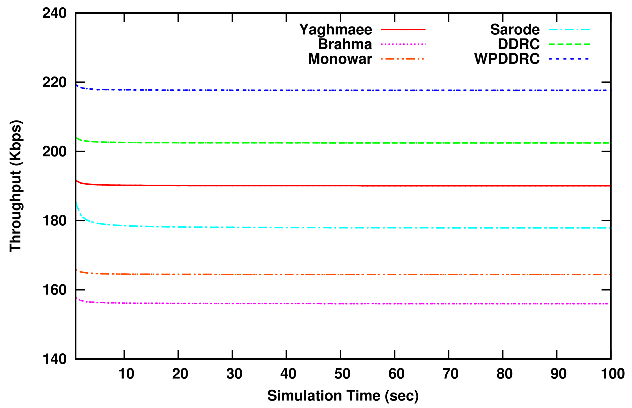

FIGURE 6. Node C1: Comparison of throughput.

For node C1, throughput of the six algorithms are shown in Fig. 6, where it may be observed that the throughput of WPDDRC is the highest while that of Brahma *et al.*'s algorithm is the lowest one. Throughput for DDRC algorithm is also enhanced and this is attributed to our proposed notion of the higher order derivative based rate control. It may be noted that the throughput is further enhanced for WPDDRC because the algorithm is based on the combined approach of weighted priority assignment and the higher order derivative control.

The above findings have also been reflected on the packet loss and the delay time as shown in Fig. 7 and Fig. 8 respectively. It may be observed from Fig. 7 that the packet loss for WPDDRC algorithm is reduced to a low value within 20 sec and attains minimum value after 40 sec. Further, it may be seen that the packet loss for Brahma *et al.*'s algorithm is less than that of DDRC and is close to that of WPDDRC algorithm. Packet loss for Monowar *et al.*'s algorithm is the highest whereas the packet loss for Sarode *et al.*'s algorithm is close to that of the DDRC algorithm and packet loss for DDRC is at intermediate value between Monowar *et al.*'s and Brahma *et al.*'s algorithm. These observations are consistent with the throughput computation. However, observations are

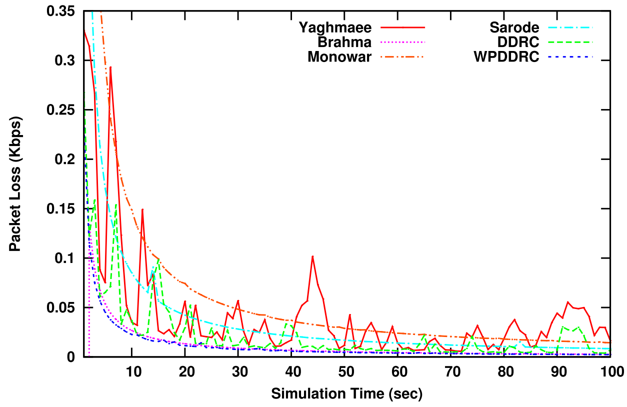

FIGURE 7. Node C1: Packet loss for different algorithms.

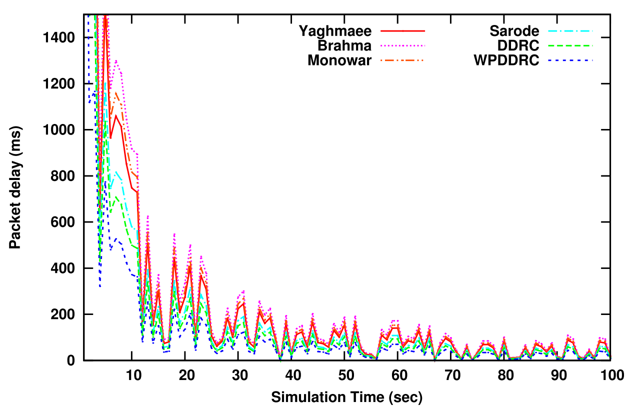

FIGURE 8. Node C1: Packet delay for different algorithms.

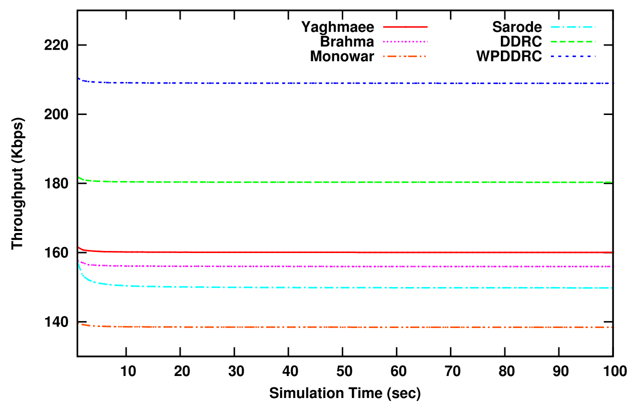

FIGURE 9. Node C3: Comparison of throughput.

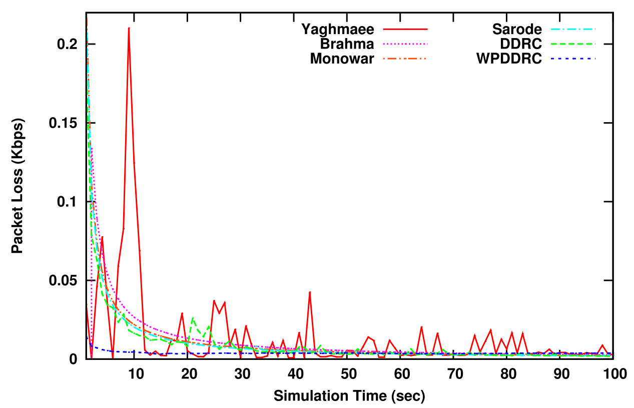

FIGURE 10. Node C3: Packet loss for different algorithms.

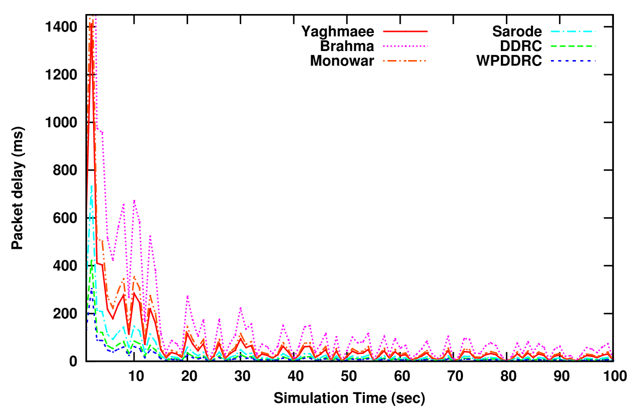

FIGURE 11. Node C3: Packet delay for different algorithms.

different for the packet delays of different algorithms as presented in Fig. 8. In this case, the packet delay is minimum for WPDDRC algorithm and delay is maximum for the Brahma *et al.*'s algorithm. This minimum delay of WPDDRC algorithm is because of the controlled priority of the traffic classes and the contribution of the difference of differentials in WPDDRC algorithm. Yaghmaee *et al.*'s algorithm has higher amount of delay than that of our proposed DDRC algorithm but lower than that of Brahma *et al.*'s algorithm. This is because of the fact that Yaghmaee *et al.*'s algorithm is based on only the notion of differentials, which is different from our proposed notion. We have also presented the throughput, loss and delay parameters of C3 child node, as the connected traffic classes to this node are different with different priorities. Three traffic classes such as RT, HNRT, and MNRT are connected to the C3 node. Throughput, packet loss and packet delays are presented in Fig. 9, 10 and 11 respectively. As observed from Fig. 9, the throughput is the highest for WPDDRC algorithm while it is the lowest for Monowar *et al.*'s algorithm. This highest level of throughput is again due to the controlled priority levels and the difference of differentials in WPDDRC algorithm. This is also reflected in the packet loss and the packet delay as shown in Fig. 10 and Fig. 11 respectively. The packet loss is minimum for WPDDRC and the variations of the packet loss over time are maximum in case of Yaghmaee *et al.*'s algorithm. It is observed that the packet loss in case of Monowar *et al.*'s algorithm is less than that of Brahma *et al.*'s algorithm. Variations in the packet loss are also observed in case of the proposed DDRC algorithm, Sarode *et al.*'s algorithm, and Brahma *et al.*'s algorithm. As far as the packet delay is concerned, the delay is maximum for Brahma *et al.*'s algorithm while minimum in case of WPDDRC algorithm. As observed, the packet delay of DDRC algorithm and WPDDRC algorithm are very close to each other.

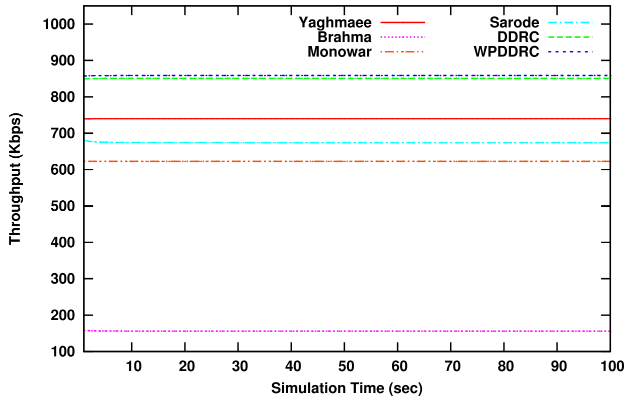

FIGURE 12. Parent node P1: Comparison of throughput.

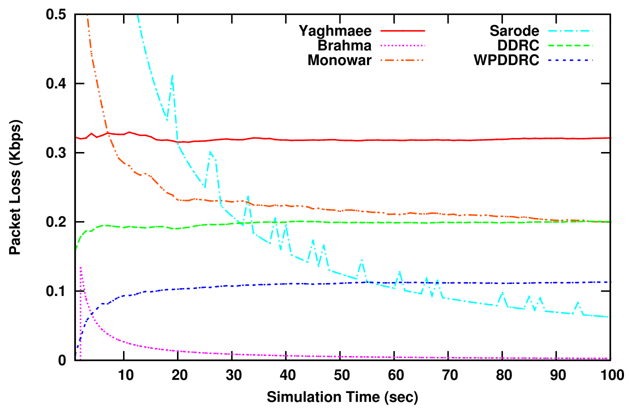

FIGURE 13. Parent node P1: Packet loss for different algorithms.

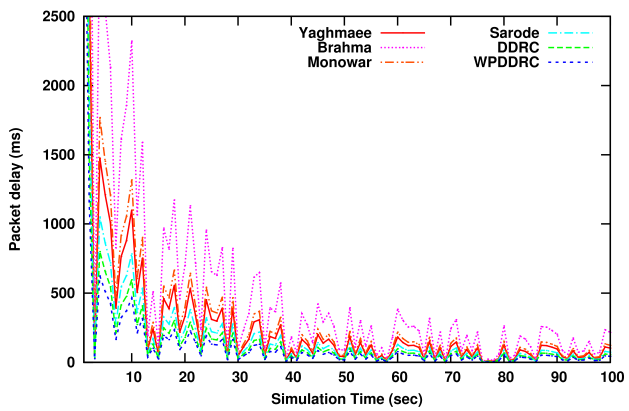

FIGURE 14. Parent node P1: Packet delay for different algorithms.

Since P1 is connected to the child nodes C1 and C3, throughput, packet loss and delay of P1 node are also presented in Fig. 12, 13 and 14 respectively. As observed from Fig. 12, throughput of P1 is high and particularly throughput is the highest for WPDDRC algorithm. The next level of the throughput is achieved by the proposed DDRC algorithm. As seen from Fig. 12, the lowest throughput corresponds to Brahma *et al.*'s algorithm, which is based on fairness only, and as expected the throughput for Yaghmaee *et al.*'s algorithm is less than those of DDRC and WPDDRC algorithms. In case of Monowar *et al.*'s algorithm, throughput is much higher than that of Brahma *et al.*'s algorithm but close to Sarode *et al.*'s algorithm. Similar observations are also made in case of the packet loss of different algorithms as shown in Fig. 13. It is found that the packet loss is maximum for Yaghmaee *et al.*'s algorithm. Initially, the packet loss is maximum for Sarode *et al.*'s algorithm but it decreases after 20 sec and thereafter is lower than that of the WPDDRC algorithm after 70 sec. As observed from Fig. 14, the packet delays for DDRC and WPDDRC algorithms are almost close to each other while Brahma *et al.*'s algorithm has the highest value. Further, it is observed that the packet delay for Yaghmaee *et al.*'s algorithm is close to that of Monowar *et al.*'s algorithm and for Sarode *et al.*'s algorithm is close to that of DDRC algorithm. Thus, it is evident that the combined effect of controlled priority and higher order derivative is not prominent on delay parameter as compared to only the higher order derivative.

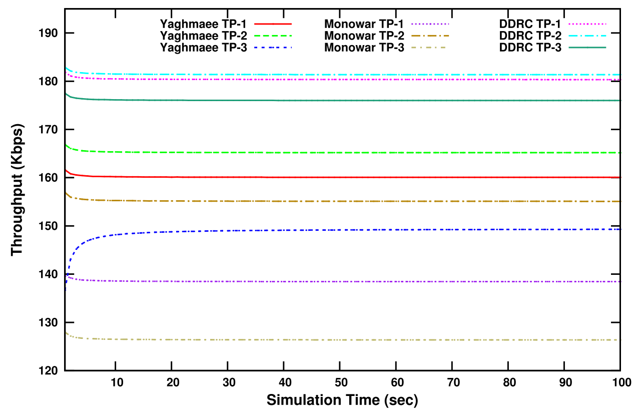

FIGURE 15. Node C3: Effects of traffic patterns for Yaghmaee et al's, Monowar *et al.*'s, and DDRC algorithms, TP1= RT+HNRT+LNRT, TP2=RT+HNRT+MNRT+LNRT, and TP3=HNRT+MNRT+LNRT.

A. EFFECT OF TRAFFIC CLASS PATTERNS AND NODE MOBILITY

1) EFFECT OF TRAFFIC CLASS PATTERNS

Since the notion of priority is absent in Brahma *et al.*'s algorithm, the study of the effect of traffic class patterns is confined to Yaghmaee *et al.*'s algorithm, Monowar *et al.*'s algorithm, Sarode *et al.*'s algorithm, and two proposed DDRC and WPDDRC algorithms. We have considered different traffic patterns at four different child nodes C1, C2, C3 and C4 and also studied the effect of these on the throughput of the child nodes and the corresponding parent node. For the sake of illustration, the different traffic patterns considered at the child node C3 are TP1, TP2 and TP3 which are defined as TP1=RT+HNRT+LNRT, TP2=RT+HNRT+MNRT+LNRT and TP3=HNRT+MNRT+LNRT. It may be noted that TP1 consists of three traffic classes whereas TP2 consists of four traffic classes and TP3 consists of three traffic classes without the high priority RT traffic class. The throughput of the C3 node for the above three traffic classes and five different algorithms are shown in Fig. 15 and Fig. 16.

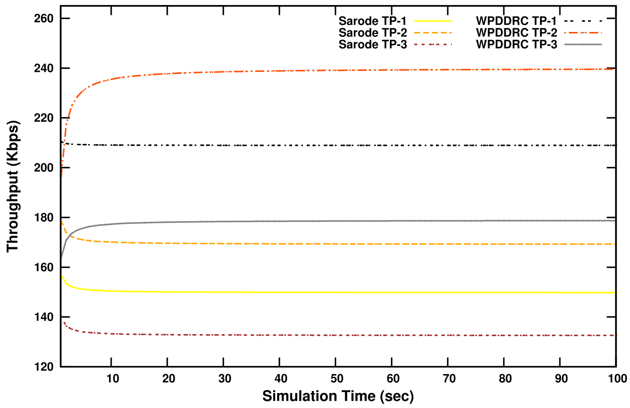

FIGURE 16. Node C3: Effects of traffic patterns for Sarode *et al.*'s and WPDDRC algorithms, TP1=RT+HNRT+LNRT, TP2=RT+HNRT+MNRT+LNRT, and TP3=HNRT+MNRT+LNRT.

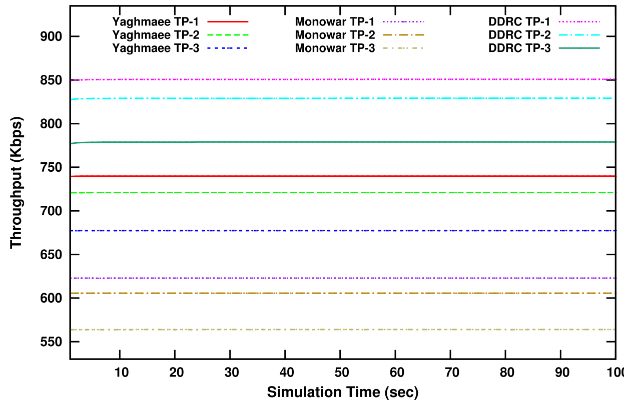

FIGURE 17. Node P1: Effects of traffic patterns for Yaghmaee et al's, Monowar *et al.*'s, and DDRC algorithms, TP1= RT+HNRT+LNRT, TP2=RT+HNRT+MNRT+LNRT, and TP3=HNRT+MNRT+LNRT.

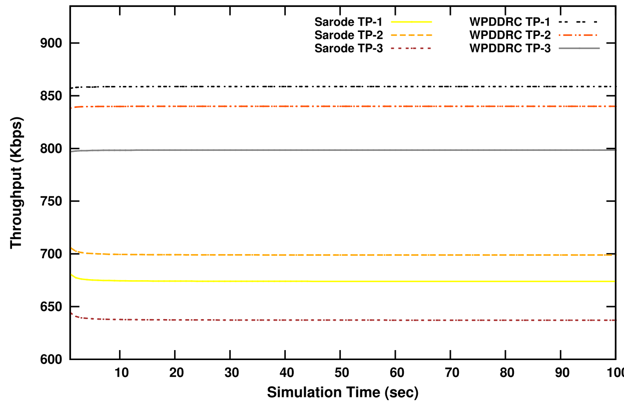

FIGURE 18. Node P1: Effects of traffic patterns for Sarode *et al.*'s and WPDDRC algorithms, TP1=RT+HNRT+LNRT, TP2=RT+HNRT+MNRT+LNRT, and TP3=HNRT+MNRT+LNRT.

From the above three different cases of the traffic pattern, the third case is having the lowest priority as there is no RT traffic. As observed from Fig. 15, three throughputs corresponding to three different patterns of Monowar *et al.*'s algorithm are at the bottom of Fig. 15. But, the throughput for TP3 traffic class is the lowest among all the traffic patterns of Monowar *et al.*'s algorithm. The next one corresponds to TP1 and the highest one of Monowar *et al.*'s algorithm corresponds to TP2. This is due to the fact that TP2 has the highest priority while TP3 has the lowest priority. Similar observations are also made for Yaghmaee *et al.*'s algorithm, Sarode *et al.*'s algorithm, DDRC, and WPDDRC algorithms. However, the throughput for all the three traffic patterns of WPDDRC algorithm are the highest among all the three algorithms. Further, it is also observed that the throughput of WPDDRC is maximum corresponding to the traffic class pattern of TP2 as shown in Fig. 16. This is again attributed to the fact that TP2 has the highest priority level. Thus, it is found that the traffic patterns do affect the throughput and specifically, as expected high throughput is recorded for the high priority data traffic.

We have also studied the effect of traffic patterns on throughput of the parent node P1, which is connected to the C3 node. The child nodes are with the three different pre-assigned traffic patterns, but the traffic pattern of parent node P1 is fixed. The throughput of P1 depends on the combined effect of the traffic patterns of the connected child nodes C1, C2, C3, and C4. As observed from Fig. 17 and Fig. 18, in case of Monowar *et al.*'s algorithm, the highest throughput corresponds to the traffic pattern TP1, and the lowest throughput corresponds to TP3. Similarly, in case of WPDDRC algorithm the highest throughput corresponds to TP1, which is same as the case of Monowar *et al.*'s algorithm. Similar observations are also made for Yaghmaee *et al.*'s algorithm, Sarode *et al.*'s algorithm, and DDRC algorithm. It is to be noted that for C3, the highest throughput corresponds to the highest priority of the traffic class pattern TP2. This is because of the fact that the throughput of P1 is affected by the combined effect of the traffic classes of connected child nodes and the traffic class connected to the parent node. In this case also, the performance of the proposed WPDDRC algorithm is the best among the four algorithms.

2) NODE MOBILITY

We have also studied the effect of limited mobility of a node on the throughput. We have allowed the child node C1 to be mobile with a mobility rate of 10 m/s in the neighborhood of the original position of C1. The throughput of C1 with and without mobility are presented in Fig. 19. As observed from Fig. 19, in case of WPDDRC algorithm, the throughput with static node is the highest, but with the limited mobility, the throughput decreases but is close to the static case. Initially, during 20 sec, the throughput increases up to 10 sec and thereafter decreases up to 20 sec and finally settles. As expected the mobility has affected the throughput but not substantially. The throughput with mobile nodes are close to that of the static nodes. Similar observations are also made in case of Yaghmaee *et al.*'s algorithm, Brahma *et al.*'s algorithm, Monowar *et al.*'s algorithm, Sarode *et al.*'s algorithm, and DDRC algorithm. In case of mobility, the proposed WPDDRC algorithm has yielded the highest throughput among the four algorithms.

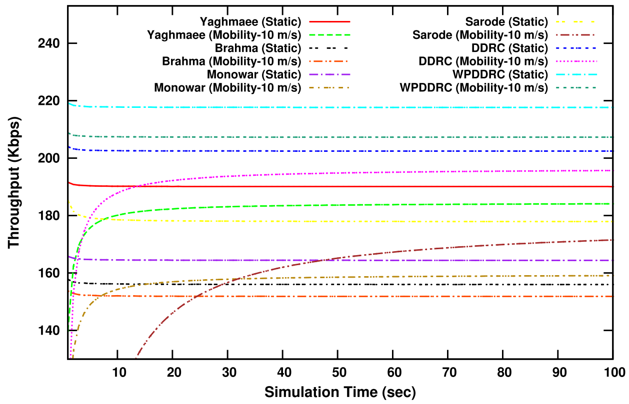

FIGURE 19. Comparison of throughput of mobile node-C1 for different algorithms.

VI. CONCLUSION

In this paper, two rate control algorithms have been proposed to avoid congestion and thereby minimizing transmission loss. The two proposed algorithms have been motivated by the notion of the priority assignment proposed by Yaghmaee *et al.* We have modified the rate control of each node of the network taking care of the higher order derivatives of rate control and also modified the GP by assigning the high priority to RT and weighted priority to the other NRT traffic classes. It is intuitively expected that the higher order differentials of the rate control will minimize the loss by increasing the throughput. This has been further reinforced by the notion of the weighted priority. Although the algorithms have been tested for a fixed topology, they are also valid for the general topology. Thus at individual nodes, the proposed rate control schemes enhance the throughput while minimizing the delay and the loss, which in turn avoids the congestion in the network. Our future work will focus on developing the rate control schemes based on the combined notion of the traffic class priority and the fair allocation of bandwidth. We will also develop congestion avoidance rate control scheme using the notion of adaptive queue management.

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