A Distributed Feedback Control Mechanism for Priority-based Flow-Rate Control to Support QoS Provisioning in Ad hoc Wireless Networks with Directional Antenna

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***Abstract*— We have proposed a scheme for supporting priority-based QoS in mobile ad hoc networks by classifying the traffic flows in the network into different priority classes, and giving different treatment to the flow-rates belonging to different classes. We have adopted a control-theoretic approach to adaptively control the low-priority flows so as to maintain the high priority flow-rates at their desired level, thus guaranteeing QoS to high-priority flow. At the same time, our objective is to adaptively maximize low priority flows while maintaining high priority flows at a desired level so that full utilization of wireless medium can be achieved through adaptive rate control. To provide this desired service guarantee to high priority flows, we need a distributed flow-control algorithm. Here, the low priority flows, causing interference to a high priority flow, detect and measure high priority flow-rate at each node on their routes and consequently adjust their flow-rates using a feedback control mechanism to maintain the high priority flow at its desired level. This detection and measurement is done at MAC layer of each node participating in routing from source to destination. We have proposed this protocol with a very nominal overhead using omni-directional antenna and modified the scheme to show the overall improvement in throughput using directional antenna. The performance has been evaluated using QualNet network simulator and the results indicate the effectiveness of our scheme.**

Keywords-Ad hoc Network; Directional Antenna; Proportional Integral Derivative Control; Flow-Rate Control

I. INTRODUCTION

The recent progress in wireless communication and personal computing leads to the research of ad hoc wireless networks, which are envisioned as rapidly deployable, infrastructure-less networks with each node acting as a mobile router, equipped with a wireless transceiver. In this context, various solutions to QoS provisioning in mobile ad hoc networks have been proposed in recent past [1]. However, limited bandwidth of the mobile radio channel prevents giving every class of traffic the same QoS. So, some means for providing each class a different QoS must be implemented by assigning priority to one class over another class [2]. Though several solutions for wired environment are present, they do not work well in wireless ad hoc networks because of shared communication environment and host mobility. In this paper, we have proposed a scheme for supporting priority-based QoS in ad hoc networks by classifying the traffic flows in the network into different priority classes, and giving different treatment to the flow-rate belonging to different classes. We have adopted a control-theoretic approach to adaptively control the low-priority flows so as to maintain the high priority flow-rates at their desired level, thus guaranteeing QoS to high-priority flow.

Several researchers have explored the idea of control theoretic approach for flow rate control in the context of wired network in order to control congestion in the network, to provide flow based end-to-end QoS as well as to deal with fairness issues. In [3], a control mechanism has been proposed that can be used to design a controller to support Available Bit Rate service, where users would dynamically share the available bandwidth in an equitable fashion, by adjusting an appropriate set of distributed controls based on feedback of explicit rates.

Two flows in ad hoc wireless network will affect each other, when the two routes belonging to these two different flows share common nodes, or, they are close enough to interfere each other, causing route coupling [4]. In this case, nodes in those two routes will constantly contend for access to the medium they share. This is shown in Fig. 1. In such a situation, if the flow-rate of low-priority flow is reduced, the high-priority flow will get more chances to access the medium they share, which eventually reduces the congestion and improves the throughput of the high-priority flow. Thus, priority-based flow control is an effective means to provide service differentiation to different class of flows.

Researchers have introduced end-to-end flow-control in transport layer to achieve service differentiation [5]. But, these schemes cannot ensure desired rates for high-priority traffic. Our objective is to adaptively maximize low priority flows while maintaining high priority flows at a desired level so that

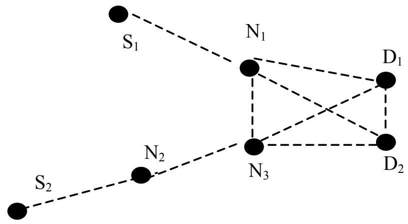

Figure 1. Low Priority Flow (S_2-D_2) is disturbing High Priority Flow (S_1-D_1) because of route coupling. Dotted Lines show omni-directional connectivity among nodes

full utilization of wireless medium is achieved through adaptive rate control. To provide this desired service differentiation to high priority flows, we need a flow-control algorithm, where the low priority flows, causing interference to a high priority flow, detect and measure high priority flow-rate at each node on their routes and consequently adjust their flow-rates using a control-theoretic approach to protect the high priority flow at its desired level. This detection and measurement is done at MAC layer of each node participating in communication. This would enable the nodes involved in low priority flow (e.g. S_2, N_2, N_3, D_2 in Fig. 1) to measure the high priority flow-rate in each of their vicinity by recording consecutive RTS reception interval from nodes involved in high-priority flows (e.g., N_3 will receive RTSs from N_1 involved in high priority flow and can measure flow-rate of high priority flow at each instant of time). This information is back propagated to S_2, the source node of low priority flow, who will compute the control decision and adjust its packet injection rate adaptively to maintain high priority flow rate at its desired level.

To implement the scheme, we have used a special type of RTS and CTS packets. There is an extra field in the RTS packet, which denotes the communication-id & priority-level of the flow to which the packet belongs. This extra field in RTS is required to make the neighbors aware of the priority-level of the on-going communication. Similarly, CTS packet also has two extra fields. The first field is exactly similar to the extra-field of RTS packet, and is required to convey the priority-level of the on-going communication to its neighbors. The second field contains the maximum packet-arrival-interval of high priority communication in its vicinity. Even in presence of more than one high priority flows in the neighborhood of a low priority flow, back-propagation of the maximum packet arrival interval of the high priority flows is done. This indicates that the low priority flow can adaptively adjust itself repeatedly, so that the high priority flows can get maximum chance to the medium and their expected packet arrival interval is maintained.

For example, in Fig. 1, let there was a continuous low-priority flow S_2-N_2-N_3-D_2. When operating alone, its flow-rate is fixed at a predefined value. Now, a high-priority flow S_1-N_1-D_1 starts. Let us assume that we want to fix and maintain this high priority flow-rate at a predefined level. However, since these two routes (Fig. 1) are close enough to cause route coupling, they will interfere each other, which will reduce the flow rate of high-priority flow at the interfering nodes N_1 and D_1. Our objective is to detect this reduced flow rate of high priority flow at nodes belonging to low-priority flow and back-propagate this knowledge back to the low priority source, which then can adaptively reduce its flow rate to maintain the high priority flow rate at its predefined value. To implement this, from the RTS and CTS transmitted by N_1 and CTS transmitted by D_1, both N_3 and D_2 detects the high-priority flow S_1-D_1. This remains unknown to the source S_2, which is far away from the high priority flow. So, with the help of CTS packet, D_2 transmits the knowledge to N_3. When N_3 has to send a CTS packet to N_2, it combines its own detection of high-priority traffic with the received knowledge from D_2 and cumulatively considers the contention in the flow and transmits it with the CTS packet. N_2 lastly sends this information back to S_2 with a CTS packet. The source node, S_2, then considers the contention in the medium of the flow and adaptively takes a decision of reducing packet injection rate. Hence, with no extra packet, the information of contention in the medium of a high priority flow is transmitted to the low priority source node, which adaptively reduces the packet injection rate. So, when there is no contention in the medium, even a low-priority flow can operate at its predefined flow rate.

Our mechanism is different from other existing MAC-layer solutions for service differentiation [6]. Several efforts have been made to support QoS in MANET by changing Inter Frame Spaces (IFS) and the size of contention window (CW) according to the priority of traffic in MAC layer and modifying *backoff algorithm* accordingly. But it does not guarantee that high priority packet will always get a contention-free access to the medium for data communication [7]. Multiple high priority flows contending for the medium may not always get guaranteed fair access of the medium in these schemes. Moreover, multiple low priority traffic in absence of high priority traffic may choose a large contention window leading to poor utilization of the medium. Another important aspect of QoS in MAC layer, which has not been addressed by the researchers, is the packet delivery ratio. Low priority packets in MAC layer of intermediate nodes may often found to choose increased backoff counter, which remains unknown to the source node, which may still be injecting packets at a very high rate. As a consequence, the packets arriving at a very high rate at intermediate node, handling low priority flow, are not served quickly by the MAC layer and remain in queue, which may overflow leading to packet drops.

What we try to achieve in this paper is a specified level of service guarantee in terms of flow rate to high-priority flows when they contend with low priority flows. We have proposed this protocol with a very nominal overhead using omni-directional antenna and modified the scheme to show the overall improvement in throughput using directional antenna.

II. A CONTROL-THEORETIC APPROACH

A. Some Preliminaries on Proportional-Integral-Derivative (PID) Control

A feedback controller (Fig. 2) is designed to generate an output u that causes some corrective effort to be applied to a process so as to drive a measurable process variable Y towards a desired value R known as the set-point. The controller uses an actuator to affect the process and a sensor to measure the results. Virtually all feedback controllers determine their output

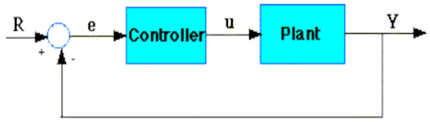

Figure 2. Basic Feedback Controller

by observing the error e between the set-point (R) and a measurement of the process variable (Y). Errors occur when a disturbance or a load on the process changes the process variable. The controller's mission is to eliminate the error automatically [8].

The general form of the PID control algorithm is:

$$u = K_P e + K_I \int e dt + K_D \frac{de}{dt}$$

The variable (e) represents the tracking error, the difference between the desired input value (R) and the actual output (Y). This error signal (e) will be sent to the PID controller, and the controller computes both the derivative and the integral of this error signal. The signal (u) just past the controller is now equal to the proportional gain (K_p) times the magnitude of the error plus the integral gain (K_i) times the integral of the error plus the derivative gain (K_d) times the derivative of the error.

Proportional gain (K_p) will have the effect of reducing the rise time and will reduce, but never eliminate, the steady-state error. An integral gain (K_i) will have the effect of eliminating the steady-state error, but it may make the transient response worse. A derivative gain (K_d) will have the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response.

The above equation is a continuous representation of the controller and it must be converted to a discrete representation and the final form of the equation is:

$$m(n) = k_p * e(n) + k_i * \sum_{k=n-w}^{n} e(k) * \Delta t + k_d * \frac{[e(n) - e(n-1)]}{\Delta t}$$

Thus it will be necessary to find the current error, the sum of the errors, and the recent change in error in order to calculate desired output.

B. Priority-Based Flow Control Strategies using PID Controller

Fig. 3 shows the basic low-priority flow-rate control (LPC) scheme where a single high priority and multiple low priority flows are coupled with each other, i.e. the routes of these flows are either sharing common node(s) or they are close enough to interfere with each other. Here, to maintain the high priority flow at a desired flow-rate R, each low priority flow is adaptively changing its flow-rate u at its source using PID control strategy, so that high priority flow rate Y becomes as close to R as possible. Nodes handling each low priority flow L_i is measuring high-priority flow (indicated by M_i), if there is a coupling with the high priority flow. This information is back-propagated to the source S_L handling low-priority flow.

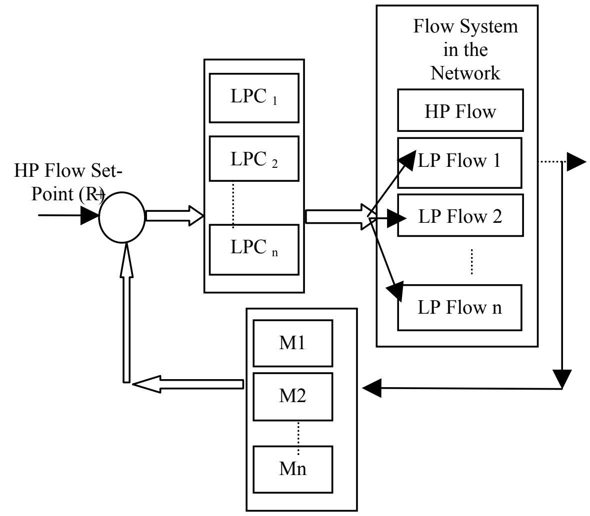

Figure 3. Flow-rate Control Scheme with Single High Priority and Multiple Low Priority flow Coupled with one another: Each Low Priority flow is using similar control scheme to protect high priority flow [LPC:=LP Flow Controller at LP Source; M_I = Measuring HP flow by nodes handling LP Flow]

From this, the source node of Li determines Y and takes a control decision using PID control. Based on this, the source node regulates the flow-rate of low-priority flow and the process is repeated.

It is to be noted that there is a subtle but important difference between conventional PID controller as illustrated before and our proposed control scheme. It can be easily seen that in our control scheme, if we set u (i.e. low-priority flow rate) to zero, Y will achieve its desired flow rate of R in the absence of any other low priority flow. So, if the focus is only on maintaining high priority flow at a desired value, the solution does not require any controller in the conventional sense of the term. However, in the present context, our objective is to maximize the low priority flow rate R_L as well, keeping high priority flow rate R_H at its desired level. This is similar to max-min flow control where our control strategy will maintain R_H at its desired level with a dynamically adjusted, controlled setting of R_L in such a manner that R_L cannot be increased further without decreasing R_H from its desired value. This kind of requirement is absent in conventional PID control and, therefore, our approach is a derivative of conventional PID control, which we will illustrate subsequently.

When multiple high priority flows are present in the system with multiple low priority flows and they are coupled, a new set point for high priority flows needs to be determined dynamically. A low priority flow will measure the high priority flow rates in their neighborhood and also get the set points of high priority flows. Accordingly, it will adjust its flow rate in order to protect the *weakest* high priority flow. Weakest high priority flow in this context is a flow having largest error value $e=(R_{new}-Y)$. This will naturally ensure the protection of other high priority flows in its neighborhood.

III. PRIORITY-BASED FLOW CONTROL SCHEME USING DIRECTIONAL ANTENNA

So far we considered omni-directional neighbors using omni-directional antenna. But, to modify the scheme using directional antenna, we have to consider a directional MAC and its directional neighbors. We have implemented in [9] receiver-oriented rotational-sector based directional MAC protocol, which is capable of tracking location of its neighbors. Thus, each node is aware of its directional neighbors and this information is recorded in its Angle-Signal Table (AST). RTS and CTS packets are omni-directional, whereas data and acknowledgement packets are directional. Use of directional antenna in the context of ad hoc wireless networks can largely reduce radio interference, thereby improving the utilization of wireless medium [4, 9]. This property of directional antenna is utilized to improve the efficiency of our protocol. This is shown in Fig. 4, where simultaneous high- and low-priority traffic S_1-D_1 and S_2-D_2 of Fig. 1 can co-exist without disturbing each other, using directional antenna, which would have not been possible using omni-directional antenna (Fig. 1). So, with directional antenna, it is not necessary for the low-priority traffic S_2-D_2 to control its packet injection rate even in presence of high-priority traffic S_1-D_1. Using directional antenna, the detection of contention in medium is also directional in the sense that even if there are traffics of different priority-level in the vicinity, only the contention from communication in the direction of flow is considered. MAC detects the directional contention in medium consulting its AST. Since directional antenna improves SDMA (Space Division Multiple Access) efficiency, it enhances the packet injection rate of low-priority flow also with minimally disturbing other flows in the medium and hence leads to increased throughput of high- as well as low-priority traffic. At the same time, chance of multiple high priority flows getting coupled will be reduced, leading to improved performance of high priority flows.

The complete distributed algorithm has been realized in four main blocks by the nodes handling low priority flow.

- The nodes hearing the special type of RTS or CTS packet transmitted by the nodes handling high priority flow detect the presence of high priority flow in the vicinity.

- The nodes hearing the RTS or CTS of the high priority flow measure the high priority flow rate (packet arrival rate at intermediate node) from the difference between two successful RTS or CTS transmission.

- The nodes handling low priority flow back-propagates the detected high priority flow rate. While back-propagating, each intermediate node combines its own detection with the back-propagated knowledge and back-propagates the most suffered high priority flow rate. If directional antenna is used, only the information of those high priority flow rates is back-propagated, which operates in the direction of low priority flow and can be affected by the low priority flow.

- The low priority source adaptively controls Packet Injection Rate of the low priority flow based on its own detection and back-propagated packet arrival rate of the high priority flow. Error e at any low priority flow L at its source node is (R-PPAI), where R is the desired high priority packet arrival interval and PPAI is the maximum packet-arrival-interval of high priority flows in the neighborhood of L. Once the error e(n) and the time interval between two successive error Δt is calculated, the Packet Injection Interval (PII) of L is calculated as

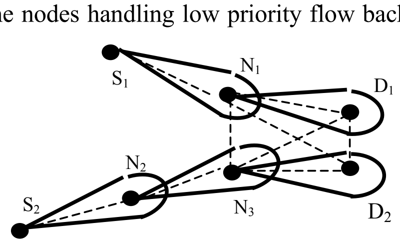

Figure 4. Using directional antenna Low Priority Flow (S_2-D_2) can coexist with High Priority Flow (S_1-D_1).

$$\mathrm{PII}(new) = \mathrm{PII}(old) - [k_p * e(n) + k_i * \sum_{k=n-w}^{n} e(k) * \Delta t + k_d * \frac{[e(n) - e(n-1)]}{\Delta t}]$$

The value of k_p, k_i and k_d needs to be tuned for optimal performance. The performance of the controller is shown in the next section.

IV. PERFORMANCE EVALUATION

We have evaluated the performance of our proposed scheme on QualNet simulator [10]. We have considered IEEE 802.11 based directional MAC [9] and implemented the proposed protocol with directional antenna only. We have simulated ESPAR antenna [4, 9] in the form of a *quasi-switched beam antenna*, which is steered discretely at an angle of 30 degree, covering a span of 360 degree.

We have used static routes in order to avoid the effects of routing protocols to clearly illustrate the gain obtained in our proposed protocol. Also, we have used static routes to stop all the control packets generated by any routing protocol. Instead of random selection of source destination pair, we have chosen the source destination pair so that there is contention between high and low priority flows to artificially create a situation so that we can demonstrate the effect of Packet Injection Interval Control.

A. Evaluating the Performance of Low-Priority-Flow-Controller (LPC)

Fig. 5 shows the performance of LPC with one high and two low priotity flows, all coupled with one another. The desired set-point R of packet injection interval (PII) of high priority flow is 20 msec, i.e. 50 packets/sec. Here, initial values of PII(H), PII(L_1) and PII(L_2) are 20msec. To show the control action of LPC, H and L_1 starts simultaneously at 30 seconds and continues till end of simulation, whereas L_2 starts at 110 second and finishes at 180 second. In the absense of L_2, behavior of LPC is same as before. But when L_2 starts, PII of both L_1 and L_2 shoot up to protect the flow-rate of H at PII(H)=20 msec. Gradually, both the low-priority flow-rate

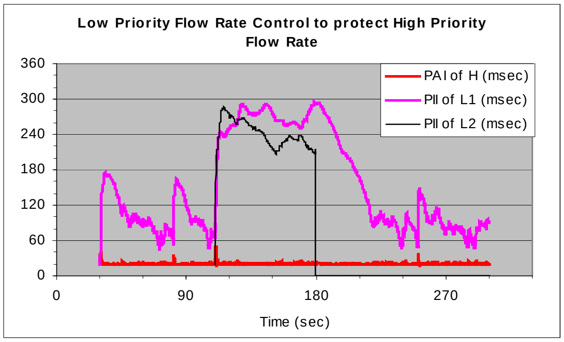

Figure 5. Adaptive Flow rate Control of two Low Priority Flows (L1 and L2) to protect the High Priority Flow (H) and maximize their own Throughput

settles down to an average PII(L)= 220 msec (approximately). After the withdrawal of L_2, PII of L_1 settles at its older value as shown.

B. *Evaluating the System Performance*

The proposed protocol has been tested and evaluated under mobility of 0-10mps to show the robustness of the proposed flow rate control scheme even in continuously changing topology. Better performance can be achieved due to the fast back-propagation of congestion information to low priority source, which can adaptively take control decision of its flow.

Fig. 6 shows the performance of a high priority traffic in our proposed flow rate control scheme under different scenarios : (i) S*ingle flow:* where a single high priority flow is operating in absence of any other flows (ii) *No LPC:* where a high priority flow is operating with other five low priority flows and no LPCs are assigned to the low-priority flows and (iii) *With LPC:* where a high-priority flow is operating with other five low priority flows and LPCs are assigned to the low-priority flows. (i) yields a Throughput of nearly 133Kbps. In (ii), the performance of this high priority flow degrades to less than one-third of its previous value. With the proposed scheme of flow rate control in (iii), throughput of this high priority flow is incremented to nearly 127Kbps. The figure also shows performance of low priority flows in two scenarios: without any priority scheme (No LPC) and after introducing the proposed packet injection rate control (with LPC). The most interesting part of the evaluation shows that after introduction of the proposed scheme, low priority flows can even improve their average throughput as well. This improvement is possible due to optimal control of packet injection rate of low priority flows, thus reducing congestion of the network, leading to optimal utilization of the medium with minimum packet loss.

V. Conclusion

We have studied the flow rate control by the detection of flows in the nodes where actual congestion is created by route coupling. Currently, we have implemented the flow control mechanism where high priority flow interacts with low priority flows. We are currently working on extending this flow rate control mechanism in cases where high priority flows contend among themselves for access to the medium. Also, by this mechanism, we are trying to improve fairness among the low priority flows when they contend among themselves for access to the medium in absence of the high priority flow.

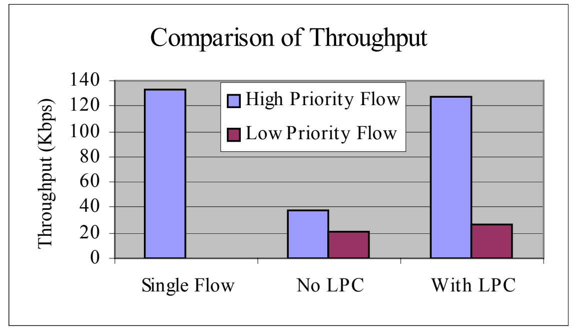

Figure 6. Comparison of Throughput of High and Low Priority flows in different scenario under mobility

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