Spectrum and Network Management Convergence for Wireless Communications

Sheetalkumar R. Doshi, Ha H. Duong, Rajive L. Bagrodia, and Serey Thai

Abstract— **The main objective of this work is to study the spectrum-network management convergence that enables spectrum efficiency while providing adequate Quality of Service (QoS) required for mission critical applications running on a wireless communication network. We combine well known QoS frameworks with the different dynamic frequency (channel) allocation approaches for spectrum management to devise mechanisms that can enable efficient spectrum-network management in wireless networks with Joint Tactical Radio System (JTRS)-like nodes. Specifically, we present two schemes: the first is 'Greedy-DiffServ' scheme which is based on DiffServ and the opportunistic (greedy) approach for dynamic frequency allocation. The second scheme is 'Shared Information-IntServ' which is based on IntServ and the shared information approach for dynamic frequency allocation. These two mechanisms are implemented in the QualNet network simulator on a hierarchical wireless mobile ad hoc network using 'JTRS-like' devices and are evaluated against an extensive set of notional scenarios. We present simulation results that highlight the advantages of deploying a spectrum-network management scheme in a wireless network and compare the performance of the two mechanisms.**

Index Terms— **Mobile wireless networks, Network Management, QoS provisioning, Radio spectrum management**

I. Introduction

EFFICIENT spectrum utilization is a primary objective of the next generation wireless communication networks being developed under multiple Department of Defense (DoD) programs. There are two significant problems confronting existing wireless communications with respect to spectrum use:

- Scarcity: The current method of allotting spectrum provides each new service with its own fixed block of spectrum. As the amount of useable spectrum is finite, it has become difficult to allocate spectrum for newly introduced services.
- Deployment difficulty: Currently, extensive frequency by frequency and system by system coordination is required for each country in which wireless systems operate. As the number, size, and complexity of wireless systems increase, the time for deployment is becoming unacceptably long.

Both problems are the result of the centralized and static nature of current spectrum allocation policy. This approach lacks the flexibility to aggressively exploit the possibilities for dynamic reuse of allocated spectrum over space and time, resulting in very poor utilization and apparent scarcity. These problems become more critical in instances where assigned spectrum is used only in certain geographical areas, or for brief periods of time. This inefficient spectrum allotment shall only increase in future as localization increases due to radio devices and the proliferation of highly bursty services that operate only for short times. Studies have determined that even a straightforward spectrum reuse method can provide an order of magnitude improvement in available capacity.

Quality of service (QoS) provisioning in wireless communication networks plays an integral part in determining the success of network-centric warfare as envisioned in future military operations. Unlike in the wired networks where bandwidth is usually abundant, bandwidth of the wireless networks, especially ad hoc networks is always scarce. Providing QoS guarantee, or at the very least some kind of differentiated services, is necessary to ensure delivery of mission-critical data.

The following question arises often in wireless networks that are spectrum resource scarce and carry real time sensitive data from mission critical applications: "How can we bring about adequate QoS provisioning for mission critical applications running on a wireless network, specifically mobile ad hoc networks (MANETs), while ensuring that spectrum resources are efficiently utilized?" One of the solutions is to employ mechanisms that combine spectrum management and network management, i.e. spectrum and network management convergence.

Extensive work has been done in the individual areas of spectrum management and network management. Numerous studies have focused on methods for QoS provisioning in wired as well as wireless networks. IntServ [25] and DiffServ [24] have emerged as standard mechanisms for QoS provisioning in IP-based networks. Other studies focus on QoS provisioning methods for wireless mobile ad hoc networks, e.g. [16], [17], [18], [19] and [22]. Specifically, in the area of spectrum management [4], [5], [6], [7], [8], [9], [10] and [14] focus on dynamic spectrum allocation (DSA).

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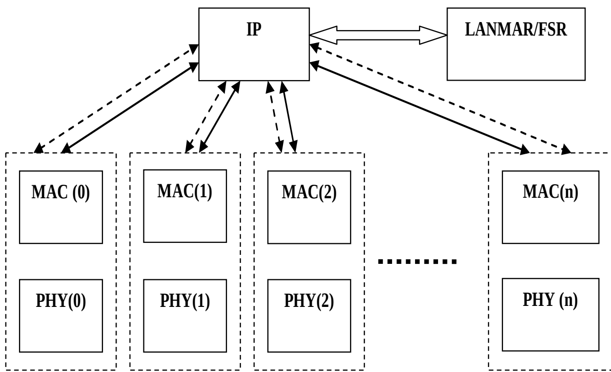

Fig. 1 JTRS-like device model. (Solid arrows represent data interaction. Dotted arrows represent cross layer interactions).

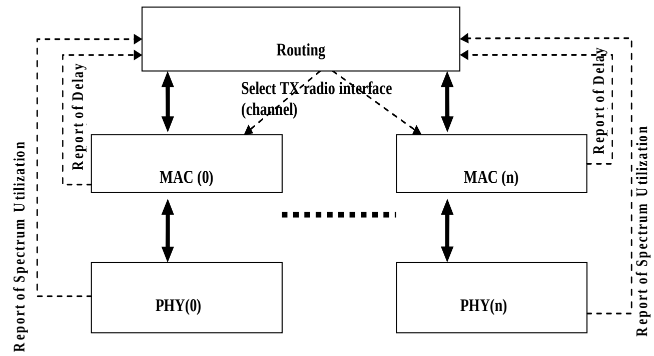

Fig. 2 Cross Layer Architecture

These studies suggest two broad approaches for dynamic spectrum allocation: one is an opportunistic (greedy) scheme for spectrum allocation based on a local view of available spectrum. The other is a cooperative, shared information scheme based on network wide information regarding available spectrum. Among the works that address efficient spectrum management, only a few have considered the interplay between spectrum sharing and QoS provisioning. Berlemann et al. [23] address the problem of adaptive spectrum sharing and QoS from a game theory perspective. The treatment of QoS is however at a very conceptual level. Thus there exist only a few studies that focus on spectrum-network management convergence.

The study of Software Defined Radios (SDRs), more precisely cognitive radios, is also key towards achieving the convergence of spectrum management and network management. Mitola [12][13] focuses on cross layered architecture of a cognitive radio in which information of one layer is made available to other layers to make decisions on resource management and parameter settings. Several other studies [1][2][3] emphasize the need of a cross layer architecture for wireless networks and propose architectures that improve performance in wireless networks.

Our work presented in this paper also employs cross layered network architecture, and merges mainstream approaches for QoS provisioning and spectrum allocation to achieve the desired spectrum network management convergence. The rest of the paper is structured as follows: Section II describes the Joint Tactical Radio System (JTRS)-like device architecture on which the proposed schemes shall be implemented. It also outlines the cross layered architecture support for the device. In the Section III, we present details of the proposed spectrum-network management schemes with analysis of the expected advantages and limitations of each scheme. In Section IV we present the performance metric used to evaluate the schemes and present simulation results that indicate the effectiveness of our proposed spectrum network management convergence in a MANET with 'JTRS-like' devices. Section V summarizes the study and discusses future work.

II. JTRS-LIKE DEVICE ARCHITECTURE

The JTRS-like device architecture is illustrated in Fig. 1. Each device consists of *n* radio interfaces with each radio operating at a distinct range of frequency. We denote a radio interface as a channel and use this definition interchangeably throughout the rest of the paper. Each radio interface has a MAC protocol (IEEE 802.11) to handle media access functions for the radio. The device has a single logical IP address and the IP layer can select one of the available radio interfaces for transmission on a per-packet basis, similar to the functionality supported by a SDR. The routing protocol running on the device is LANMAR/FSR [20], [21], a hierarchical routing protocol.

A. Cross layer interactions

Based on the device model described in the previous section, we design cross-layered interactions between physical and routing layer and between MAC and routing layer as illustrated in Fig. 2. These interactions are enabled through the following steps:

- Measurement/ Estimation/ Computation of relevant statistics at the underlying layers i.e. MAC and physical layers and export of these relevant statistics to the overlaying layer
- Integration of the statistics into the decision making processes of the overlaying layers.

In the following section, we will describe these steps in detail.

B. Measurement and estimation of statistics at physical layer

The statistic of interest at the physical layer is the **spectrum utilization/ available bandwidth** which estimated as following for each radio interface:

- Each radio interface continuously monitors the channel activities for a period of time (i.e. sampling interval $T_{Sampling\_PHY}$), and measures the idle time (T_{Idle}) during this interval
- Evaluate the current spectrum utilization ($U_{current}$) over the sampling interval as:

$$U_{current} = 1 - \frac{T_{Idle}}{T_{Sampling\_PHY}} \quad (1)$$

- To average out instantaneous effects, the previous measurement ($U_{previous}$) is also taken into account, resulting the estimation of spectrum utilization as following:

$$U_{estimated} = \alpha U_{presvious} + (1-\alpha) U_{current} \quad (2)$$

where α is a weight coefficient with the range (0, 1).

- The radio interface sends a report of estimated spectrum utilization including $U_{estimated}$ to the routing layer.

C. Measurement and estimation of statistics at the MAC layer

The statistic of interest in the MAC layer is the **average packet delay for successful transmission**. This delay is measured from the moment of packet arrival from the IP layer until reception of acknowledgment for the successful transmission. In general, the delay includes queue delay, transmission delay for the packet (back off time and transmission time), and transmission delay for acknowledgment. We define steps for measurement and estimation of the packet delay as following:

- Measure delay for each packet by noting packet arrival time and time of acknowledgement reception.
- Calculate the current average value of delay ($D_{current}$) over a certain sampling interval ($T_{Sampling\_MAC}$).
- To average out instantaneous effects, the previous measurement ($D_{previous}$) is also taken into account, resulting the estimation of average delay as following:

$$D_{estimated} = \beta D_{presvious} + (1-\beta) D_{current} \quad (3)$$

where β is a weight coefficient, with the range of (0, 1).

- The MAC sends the report of estimated average delay including $D_{estimated}$ to the routing layer.

D. Usage of the statistics at the network/routing layer

At the network layer, the statistics of information from each radio interface is an input to the spectrum-network management schemes. The following is an example of the usage of the statistics:

Assuming a packet flow requires QoS provisioning expressed as bandwidth B_r and delay D_r, the network layer will map the QoS requirement to the estimated statistics (e.g. estimated spectrum utilization $U_{estimated}$ and packet delay $D_{estimated}$) to select the channels satisfying the requirement. The routing protocol can also incorporate the statistics into the routing table and uses them as one of factors to make routing decisions.

The next section details the spectrum-network management schemes that utilize these statistics to make decisions on spectrum allocation and QoS provisioning.

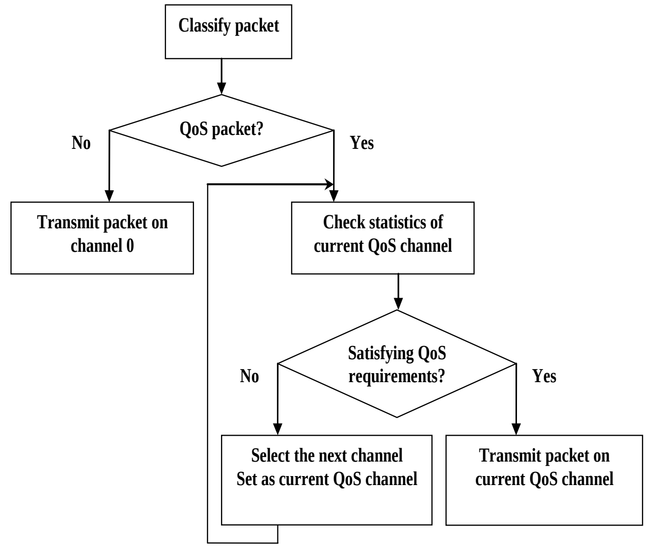

Fig. 3 Greedy DiffServ scheme: packet classification and channel selection.

III. SPECTRUM-NETWORK MANAGEMENT SCHEMES

We present two schemes with different approaches for achieving the spectrum-network management convergence, namely: Greedy-DiffServ (GD) and Shared Information-IntServ (SII).

A. Greedy-DiffServ scheme

This scheme is built on the approach of opportunistic frequency allocation. This approach responds to a changing radio frequency environment by automatically adapting its transmissions to zones where no other systems are operating. The basic approach first senses the spectrum to determine where other systems are operating and where idle spectrum exists and then synthesizes a waveform to exploit the idle spectrum. Thus, an adaptive system enables operation with other radio systems in non-cooperative fashion and potentially increases the utilization of the spectrum. Such a system can also share knowledge of the spectrum environment with other similar devices to ensure other users are not affected by the adaptive system. Besides the inter-operation with other systems in underutilized spectrum, adaptive spectrum systems may also increase spectrum utilization since they do not rely upon static frequency assignments. Underlying this form of opportunistic adaptive assignment is the assumption that spectrum is not always used across the dimensions of the spectrum space, especially frequency and time. DARPA's next Generation (XG) program [14] employs the opportunistic approach for dynamic frequency assignment.

The GD scheme applies the DiffServ principle to differentiate packets with different required QoS as shown in Fig. 3. Currently, we assume only two types of packets, non-QoS packets (including control and best effort packets) and QoS packets (that may have different QoS requirements). The channel 0 (i.e. MAC 0 and PHY 0) is reserved for transmission of non-QoS packets, therefore it is called non-QoS channel. Other channels (1, 2, … , n) are used to transmit QoS packets, hence called QoS channels. The QoS channel

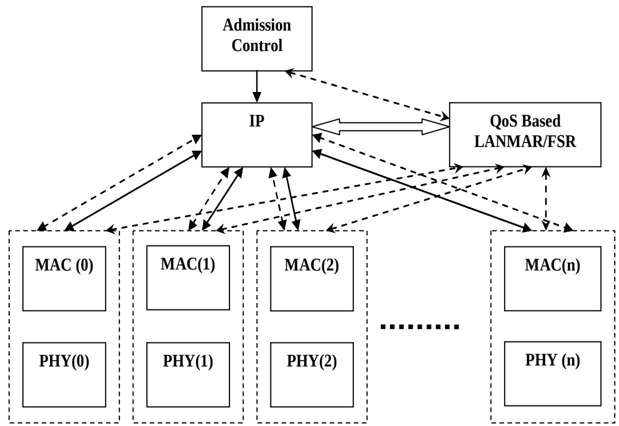

Fig. 4 Modified architecture for Shared Information-IntServ scheme (Solid arrows represent data packet interaction, dotted arrows represent cross layered interaction).

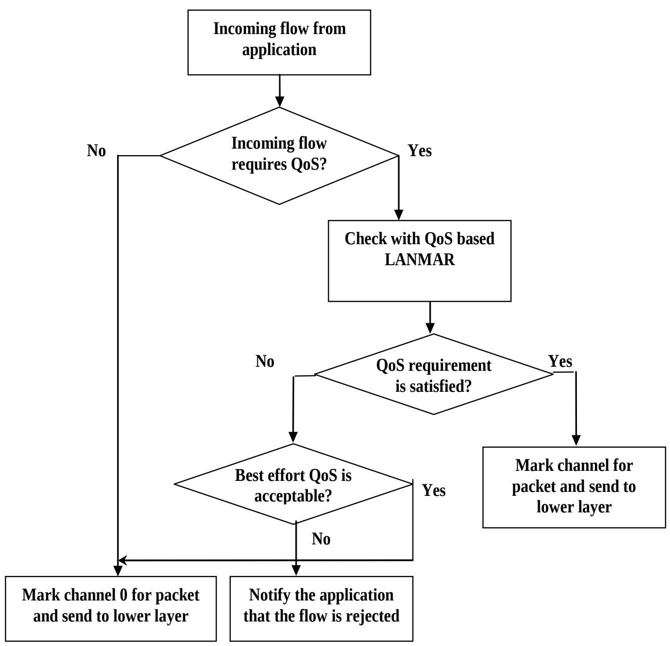

Fig. 5 Shared information scheme: Admission control at source node

selection logic is as follows: the scheme selects the first QoS channel starting from 1 that satisfies QoS requirement. As the selection is on per packet basis, QoS packets from the same flow may be transmitted on different channels. It is noted that the greedy scheme is responsible for selection of QoS channel, not selection of next hop (i.e. route). Therefore, a routing protocol (in our study, it is LANMAR/FSR) is still required to find and maintain the minimum hop route from a source to a destination. Since end-to-end channel statistics information is not considered in channel selection, the greedy scheme may not achieve the optimum spectrum utilization on global scale. However, the advantages of this scheme are its low complexity, no packet overhead and minimal modification of the protocol stack, thus leading to ease of implementation.

B. Shared Information-IntServ scheme

The SII scheme is based on the second approach for dynamic frequency allocation, which exploits *shared information* to *cooperatively* determine spectrum access

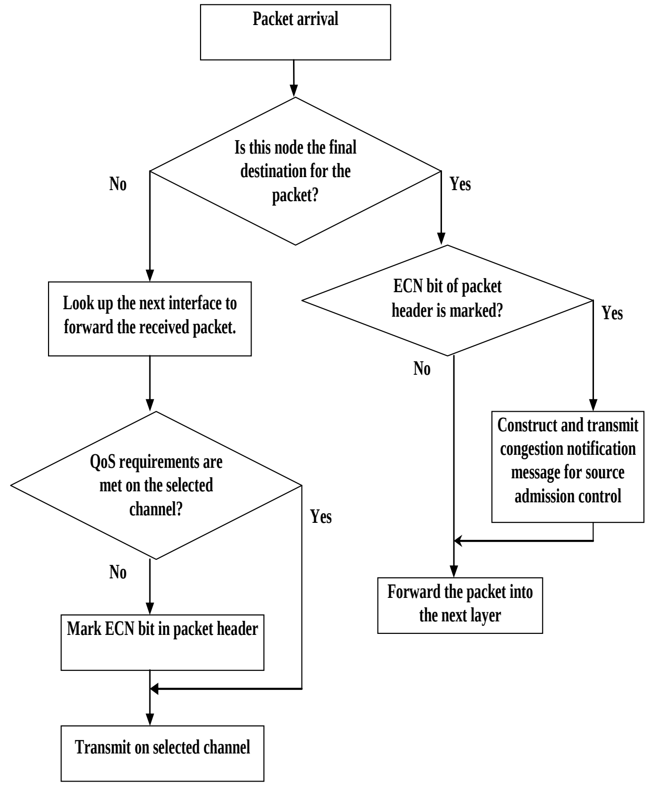

Fig. 6 Shared information scheme: Processing packets at forwarding/destination node

criteria. Such a scheme is already present, though in a limited manner, in existing systems like trunked radio systems that share channels between users and cellular systems that assign channels to users (either time slots or CDMA codes). Unlike opportunistic approaches, sharing information can greatly improve spectrum access utilization by coordinating access across the various spectrum dimensions. The SII scheme applies the IntServ principle to provide end-to-end QoS. For each flow requesting QoS, the scheme conducts admission control, and if accepted, reserves **a channel** for end-to-end transmission of packets of the flow. To make the decision, the scheme uses the spectrum utilization information of the entire network shared via the routing protocol. Once a channel is reserved for a flow, all packets of that flow are transmitted on the reserved channel. In case the flow violates QoS agreement at any hop, the Explicit Congestion Notification (ECN) bit of the IP header of packets is marked. Upon reception of the "marked" packets, the destination sends an explicit congestion notification message to the source to report to its admission control regarding the violation. This prompts admission control to suspend the current channel assignment for the flow and carry out reassignment of a new channel, if possible. Thus the shared information from various nodes in the network allows for admission control to be aware of network changes in terms of topology and utilization and allows tighter control on the allocation of spectrum resources. The scheme uses the routing protocol to collect and disseminate the information across the network. This requires modification of the LANMAR/FSR protocol and the modified protocol is denoted as QoS based LANMAR/FSR. A similar modification of

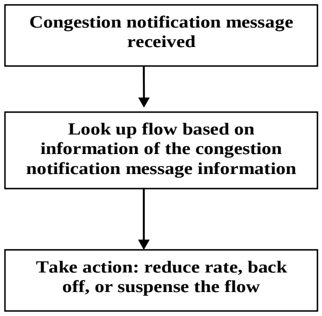

Fig. 7 Processing the congestion notification message

LANMAR/FSR has been used in [22].

The architectural view of the SII scheme is shown in Fig. 4, where we show interactions between interfaces, IP, admission control and QoS based LANMAR/FSR. The scheme itself includes two parts, operation of admission control and operation of packet forwarding as illustrated in Fig. 5 and Fig 6. During the operation of admission control, non QoS flows are always slotted into channel 0, and QoS flows, if accepted, are slotted into channels using the following logic:

- Lookup statistics for each channel for the minimum hop path to the destination using QoS based LANMAR/FSR tables.
- Select the channel for the flow only if end-to-end constraints may be satisfied for that channel based on the information obtained.
- Note channel and flow information in the admission control table.

This flow-based admission control and channel allocation applies implicit resource allocations in terms of bandwidth for each flow. Admission Control marks packets belonging to admitted flows with the channel to be transmitted on, and then the IP layer passes the packet to that channel.

During the operation of forwarding a QoS packet, intermediate routers check the statistics of the channel on which packet is to be forwarded. If the channel no longer satisfies QoS requirement, the packet is still transmitted, but ECN bit in the IP Header of the packet is set. On receiving the packet at the destination, this ECN bit is checked and if set, a notification packet is constructed and sent to the source as shown in Fig. 6. Upon reception of the message, the source node will take an appropriate action as illustrated in Fig. 7.

The main advantage of the SII scheme is tighter control on the use of spectrum and QoS provisioning over entire network. However, it comes at cost of complexity, protocol modification (QoS enabled LANMAR/FSR) and overhead for congestion notification packets.

IV. PERFORMANCE EVALUATION AND RESULTS

To evaluate the proposed schemes, we employ a performance metric called QoS spectrum efficiency to measure how efficiently spectrum is used towards achieving QoS provisioning. This metric can also be denoted as QoS Packet Delivery Ratio (PDR) per channel or normalized QoS PDR. This metric is expressed as the ratio of QoS PDR to the total spectrum used by the network. The QoS PDR is defined as the ratio of the number of QoS sensitive packets delivered to destination with acceptable delay to the total number of such QoS sensitive packets sent. We present a performance comparison of three wireless networks: one employing the GD scheme, one employing the SII scheme and one without any spectrum-network management scheme. This comparison highlights the advantages of deploying a spectrum-network management scheme in a wireless network and also indicates scenarios in which one spectrum-network management scheme outperforms the other.

A. Simulation Model

We used the QualNet network simulator [26] to implement and evaluate the proposed spectrum-network management schemes. The evaluation scenario consists of 52 nodes randomly divided into four mobility groups and distributed in area of 1500m x 1500m. For this study, we consider three levels of mobility of the nodes:

- stationary
- slow mobility at walking speeds of 1 m/s
- medium mobility at slow moving vehicle speeds of 5m/s

Each simulation was executed for 10 minutes of simulation time. The traffic load in the scenario is generated by 300 Constant Bit Rate (CBR) flows which signify the QoS load. For each of the flows a source-destination pair is randomly selected. The size of a CBR payload is 512 bytes. To generate different traffic loads, we vary the CBR packet rate, while keeping number of flows (i.e. 300) constant. In this simulation, the network wide load varies from 1 Mbps up to 10 Mbps.

In the three wireless networks, we employ JTRS-like nodes having number of radio channels n = 6, each of them operates its own IEEE 802.11 MAC and can support a data rate of 12 Mbps. For all the three wireless networks, channel 0 is used for non QoS and control packets, while other five channels are open to use only for QoS packets. In the network running no spectrum-network management scheme, we assume that the network follows random selection (RS) logic for selecting the channel on which a QoS packet is transmitted on. We denote this network as the RS wireless network. We denote the wireless networks running the GD and SII schemes as the GD network and SII network respectively.

B. Simulation Results

First, we compare the QoS PDR of the wireless networks for the stationary mobility case. A QoS sensitive packet is said to be delivered successfully if the end-to-end packet delay is less than 100ms. The results are shown in Fig. 8. Under the range of load variation from low load to high load, the three networks show similar performance. The QoS PDR for all the three networks are in the range of 0.96 to 1. This indicates that RS, GD and SII wireless networks satisfy the objective of

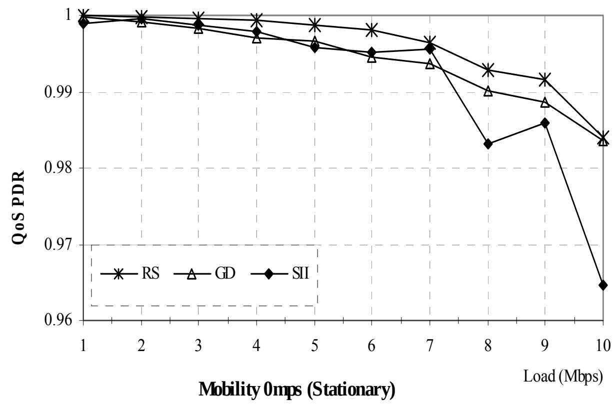

Fig 8 QoS PDR for GD, RS, SII networks Vs Load for stationary mobility.

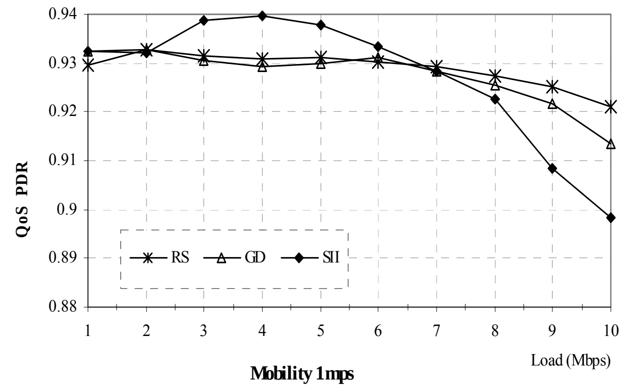

Fig. 10 QoS PDR for GD, RS, SII networks Vs Load for mobility 1m/s

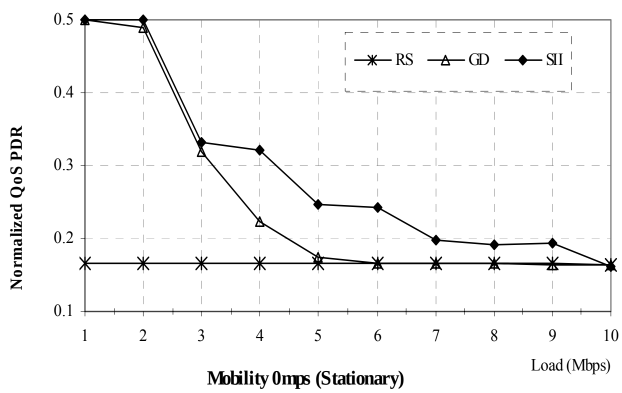

Fig. 9 Normalized QoS PDR for GD, RS, SII networks Vs Load for stationary mobility.

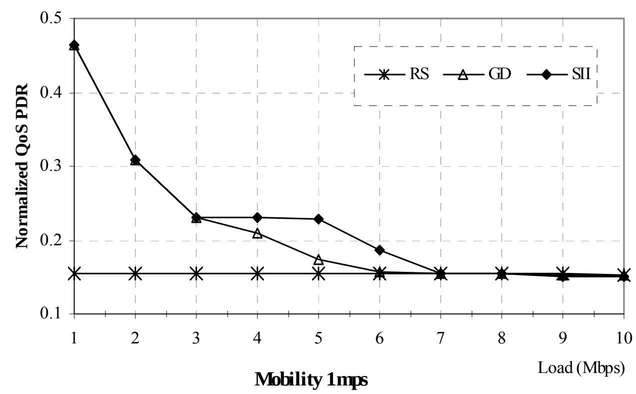

Fig. 11 Normalized QoS PDR for GD, RS, SII networks Vs Load for mobility 1m/s.

achieving a high value of QoS PDR over varying load conditions.

The reader recalls that the metric of prime interest is the QoS PDR per channel (a.k.a. normalized QoS PDR, QoS spectrum efficiency) as it shows the effectiveness of spectrum utilization towards QoS provisioning. Fig. 9 shows the QoS PDR per channel corresponding to the results in Fig. 8 for the stationary case. Overall results indicate that both the GD and SII networks exhibit better performance as compared to the RS scheme in terms of efficient spectrum utilization while providing similar level of QoS. Under light load (i.e. 3Mbps and below), both GD and SII schemes perform equally well. For network load from 3Mbps to 10Mbps, the SII scheme performs better than GD scheme. This is attributed to the fact that the SII scheme has better control over spectrum resource allocation via its use of flow based admission control, which plays out in favor of the SII scheme under high load conditions. At high values of load around 10Mbps, all three schemes converge to similar performance.

As mobility is increased, it can be observed for the cases of 1m/s (Fig. 10) and 5m/s (Fig. 12) that the QoS PDR for all the three networks declines as compared to the stationary case. From a QoS spectrum efficiency perspective, the normalized QoS PDR results for 1m/s mobility case (Fig. 11) indicate that both the GD and SII network still perform significantly better if not the same as compared to the RS scheme. For low loads up to 3Mbps, SII and GD networks show the same performance. For network load from 3Mbps up to 7 Mbps, the SII network still performs better than the GD network. Beyond 7Mbps, all three networks converge to similar performance. The results for the 5m/s case (Fig. 13) indicate that the SII network is more affected by the increase in mobility since its normalized QoS PDR is now lower than the GD network for low load cases. Due to mobility, the topology and channel utilization information changes frequently and since SII scheme relies on network wide utilization information for its decisions, its performance degrades with increasing mobility. The GD scheme relies on only local utilization information; hence increasing mobility does not affect its performance significantly. For loads beyond 5Mbps for 5m/s mobility, the three networks converge to similar performance. From the above results, the following can be summarized regarding the QoS spectrum efficiency of the networks:

- For cases where both network load and mobility are low (up to 3Mbps load, mobility between 0 to 1m/s), both GD and SII networks perform equally well and significantly better than the RS network. Thus employing either of the proposed spectrum-network management schemes in such scenarios clearly improves the performance of the network.
- For cases where network load is high (3Mbps to 10Mbps) and mobility is low (0 to 1m/s), the SII network shows better performance than the GD and RS networks. Employing the SII scheme in such scenarios significantly

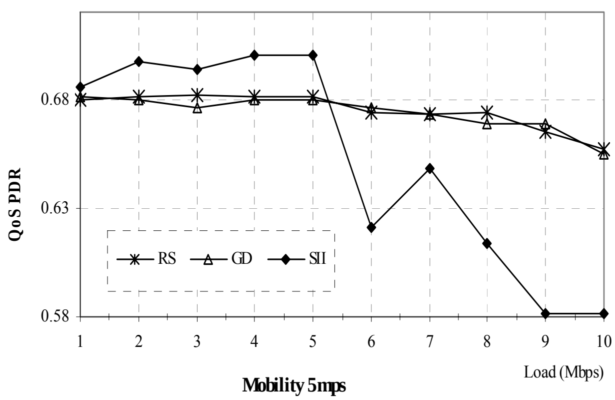

Fig. 12 QoS PDR for GD, RS, SII networks Vs Load for mobility 5m/s.

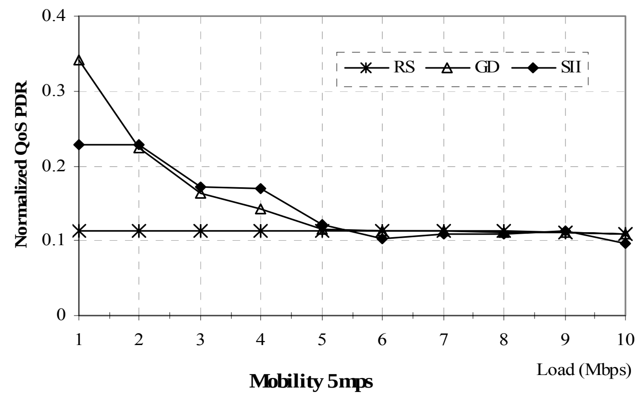

Fig. 13 Normalized QoS PDR for GD, RS, SII networks Vs. Load for mobility 5m/s.

improves the performance of the network.

- For cases where network load is low (upto 3Mbps) and mobility is high (5m/s), the GD network shows better performance than the SII and RS networks. Employing the GD scheme in such scenarios improves the performance of the network significantly.
- For cases where network load is high (5Mbps to 10Mbps) and mobility is high (5m/s), all three networks perform equally. Employing any of the proposed spectrum network management schemes in such scenarios shall not significantly improve the performance of the network.

V. CONCLUSION AND FUTURE WORK

In this paper, we present new spectrum network management schemes based on cross-layer interaction, dynamic spectrum allocation and two well known QoS frameworks, namely DiffServ and IntServ. In the schemes, the information of PHY and MAC layers activities (i.e. channel utilization and packet delay) are regularly collected and reported to the routing layers to make decisions on channel selection. Two schemes are introduced, namely, Greedy DiffServ (GD) and Shared Information IntServ (SII). The GD scheme exploits opportunistic channel allocation and differentiates packets based their QoS requirement, while the SII scheme shares information of channel utilization over the network to allocate an end-to-end channel for a QoS flow. The results indicate that better QoS spectrum efficiency can be achieved by deploying the spectrum network management schemes and the choice of scheme to be deployed depends upon the scenario characteristics. Current work in progress focuses on evaluation of the GD and SII schemes for varying network sizes and node density. Future work includes extending the schemes to accommodate different QoS classes. We also plan on designing a hybrid spectrum network management scheme that shall combine the advantages of the SII and GD schemes.

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