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Stability and performance analysis of randomly deployed wireless networks

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ABSTRACT

A growing demand for mobile services is taking the deployment of wireless local area networks away from the notion of carefully planned and carefully managed settings into randomly deployed and independently managed (if at all) network settings. This results in contentious networks that serve highly mobile nodes. In fact, research reveals that in most metropolitan cities in Europe and the US the size of closely located and contentious access points is overwhelmingly high (in the order of thousands). Subsequently, the performance of these networks is often unstable and unpredictable. This paper aims to investigate the extent of performance fluctuations in randomly deployed networks. It also aims to investigate the contribution of various adaptation strategies at different abstraction layers to deal with these fluctuations. We present the outcome of an exhaustive simulation for different applications, including VoIP, HTTP, and FTP. We will demonstrate that collision due to hidden-terminals is a minor influence on the performance and stability of these networks, whereas dynamic channel allocation greatly affects them. Moreover, HTTP applications are less affected by both inter- and intra-channel interferences compared with FTP and VoIP applications.

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1. Introduction

The use of wireless devices and networks is becoming a large-scale universal communication phenomenon. An annual report by InStat[1] reveals that more than 294 million Wi-Fi capable consumer electronics (CE) were sold in 2007 alone. The same report infers that Wi-Fi capable devices will surpass mobile PCs by 2011 and the compound annual growth rate of these devices will rise to 26% by 2012. A similar report by ABI research [18] reveals that the global growth of Wi-Fi hotspots in 2008 is estimated to be 40% higher than in 2007. The greatest growth and the largest number of hotspots are observed in Europe. Moreover, the study suggests that the dominant form of networking connectivity for consumer electronics is likely to be Wi-Fi as the most widely used type of consumer-installable and retail-based networking.

Likewise, an annual global survey by AT&T Economist Intelligence Unit[2] reveals that mobile use is most extensive among senior management in Europe and by 2010, “the business use of mobile phones and other [Wi-Fi capable] devices by management and sales staff will be nearly universal and is expected to escalate among customer service, information technology (IT), marketing staff and field workers.” The report concludes that increased workforce productivity is viewed as the key benefit of mobility.

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[1] Source: InStat: http://www.instat.com.

[2] Source: AT&T Economist Intelligence Unit: http://www.att.com.

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While this remarkable proliferation enables the pervasive availability and use of wireless networks, it brings with it some formidable challenges as well. To begin with, most of the networks should operate in a license free radio spectrum that is already in an extensive use. Secondly, while some of the networks are carefully planned (with respect to cell layout, spectrum reuse, and coverage) and centrally managed, a good portion of them are randomly deployed and independently (if at all) managed networks. Thirdly, because the nodes that potentially associate with these networks are mobile, it is hard to predict network density and performance and to guarantee quality of service. All these factors, summed up with the inherent challenges that arise due to attenuation and fading, prohibit randomly deployed wireless networks from achieving good and predictable performance and from efficiently utilizing available resources.

Several strategies have been proposed to improve service qualities, including adaptation of transmission power, dynamic channel allocation, and dynamic rate adaptation. While the approaches are useful, they have their own limitation. Even when they are effective, it is usually at the expense of energy efficiency. For example, increasing the transmission power of an access point may increase SNR, but this will have little effect if contending access points do just the same, resulting in no net gain in the SNR. Moreover, even if there is a gain with this strategy, it is achieved by inefficiently utilizing energy. There are also other concerns such as unstable or unpredictable performance.

The aim of this paper is to investigate the performance of randomly deployed networks when different types of applications (HTTP, FTP, and VoIP) run on a terminal. We adopt different strategies to investigate the net gain in throughput and the enhancement in energy efficiency. As a visualization scheme, simulation is used. Moreover, the simulation can be used to demonstrate the scope and usefulness of some of the existing strategies that are proposed to meaningfully utilize a shared channel. This investigation will be a basis for applying self-managing strategies [12,19] in these types of deployment settings to enhance performance and to ensure stable operation.

The rest of the paper is structured as follows. In Section 2 related work is presented. In Section 3 the network model and the deployment settings are presented. In Section 4 the simulation environment and the simulation results are presented in detail. Finally, in Section 5, a concluding remark will be given.

2. Related work

A substantial body of work exists on optimizing the throughput and improving the performance of wireless networks. In the context of IEEE 802.11 wireless local area networks, the most significant factors that affect throughput and performance are interference, collision and congestion. Accordingly, in the literature, there are many approaches to mitigate these problems at the physical and link layers.

Panichpapiboon et al. [16] investigate the relationship between transmission power, data rate and node spatial density; and provide a model for computing the optimal transmission power that guarantees minimum interference. Felegyhazi et al. [8] consider the co-existence of multiple networks that compete for a shared resource and propose a game theoretical approach for nodes to maximize throughput. The approach enables nodes to intelligently choose the channels that offer the optimal data rate. Even though direct collaboration between contending nodes is not supported or foreseen, the approach implicitly assumes the possibility of channel reallocation for the networks to be in a Nash Equilibrium.

The analytic model of Bianchi [9] provides an exhaustive quantitative account of the saturation throughput performance of IEEE 802.11 networks that apply the distribution coordination function (DCF) – a carrier sense multiple access scheme with collision avoidance mechanism. The model's strength is in its description of the way binary-slotted exponential back-off mechanisms impact the network's overall throughput. However, the model is most accurate for finite number of nodes and an ideal channel condition. The model of Malone et al. [14] improves the Bianchi model by considering more realistic networks in which the data traffic is considered to be non-saturated and packet arrival rate is non-uniform. The model enables to estimate the peak throughput. The analytic model of Kumar et al. [13] is similar to that of Malone et al. but it considers additional aspects such as channel access rate and models the back-off by a discrete time Markov chain (DTMC). Likewise, Bruno et al. [2] analyze the efficiency and energy consumption of wireless networks employing a *p-persistent* carrier sense multiple access scheme. Their model establishes a relationship between node density, collision rate and packet loss such that the optimal p – a parameter that determines the average size of the contention window – can be computed. The analysis result shows that besides maximizing throughput, p minimizes also the network's energy consumption. More recently, Dong and Dargie [6] provide a more accurate model of the collision probability in unsaturated situation.

Most existing or proposed contention based approaches assume that all nodes abide by the back-off rule whenever a collision occurs. However, Felegyhazi et al. [7] consider the existence of nodes that fail to exercise random deferment (exponential back-off). Their approaches enable to estimate worst case performance.

Akella et al. [1] provide a comprehensive statistical analysis about the performance of spontaneously deployed networks. Their observation – based on a large size data collected from many metropolitan cities in the US – reveals that interference is the main cause of service degradation and inefficient power consumption. Subsequently, they propose two algorithms for dynamic rate adaptation and transmission power control. The rate adaptation algorithm is an enhancement of the Auto Rate Fall-back (ARF) algorithm [20], which attempts to select the best transmission rate based on ACK packages. ARF assumes that a failed transmission is an indication of a rate that is too high and should therefore be lowered (by the same token, a successful transmission is assumed to be an indication of a transmission rate that can be upgraded). Akella et al. introduce a threshold to the ARF protocol. The threshold determines the number of consecutive packets that should be sent successfully

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before a node selects the next higher transmission rate. The same concept of threshold is applied for a node to reduce the transmission rate.

Rate adaptation algorithms perform well when packet losses are due to poor channel conditions, multi-path effects, or fading, but not necessarily when packet losses are due to congestion or hidden terminals [11]. An explicit, peer-to-peer coordination is proposed in [17] for improving the use of a licensed spectrum. The approach enables a license holding device to grant admission to a non-licensed device to use the spectrum whenever the former is idle. For coordination to take place, the unlicensed device should provide the licensed device with information pertaining to its required bandwidth, signal to interference ratio (SIR), transmission power, and location.

The main contribution of this paper is its close observation of the stability and performance of randomly deployed networks by considering some of the proposed approaches in this section as set up and management strategies. Our main focus is on the physical, link and applications layers. At the physical layer, channel allocation, transmission rate, and transmission power are investigated. At the link layer, the contribution of control packets to minimize collision and the cost incurred by control packets is investigated. At the application layer three different types of applications, namely, HTTP, FTP, and VoIP, are considered.

3. Network setup

The performance of a wireless network depends on various factors and network parameters [22]. At the physical layer, interference is the main cause of performance degradation but there are techniques that enable dynamic channel allocation and rate adaptation as well as control of transmission power. One of the main challenges at the link layer is contention and the resulting packet collision and packet retransmission [6]. To deal with this challenge, there are collision avoidance techniques in place but most of them employ control packets which can reduce the net useful data throughput. The decision to use control packets should, therefore, take several factors into account – such as node density, the type of applications that access the network, and the quantity of packets generated. For example, an empirical study on planned and centrally managed IEEE 802.11 based wireless local area networks shows that most networks by default disable the collision avoidance techniques [1] – when a collision occurs, packets are retransmitted.

We aim to investigate whether such strategies apply to randomly deployed networks. At the application layer, different applications with different quality of service requirements (bandwidth, transmission rate, jitter, delay) are considered. The applications are FTP (representing an “aggressive” traffic that attempts to seize the medium for a long time); VoIP (traffic with stringent delay and jitter requirements) and HTTP (representing a bursty traffic of short duration).

At the link layer, we consider different network setups, both with and without control packet overhead:

1. where the various access points of independent networks are able to allocate channels that are not occupied;
2. where there is an arbitrary allocation of overlapping channels between independent access points; and
3. where there is a hybrid channel allocation in which some access points occupy non-overlapping channels while others share channels.

3.1. Network deployment

Our network deployment model establishes the basic assumptions as regards to the distribution of nodes, the node density and the different types of constraints at the application, the link and the physical layers. The setting in which the randomly deployed networks operate is modeled as a 2-dimensional Poisson distribution process (Fig. 1) [3,15], and [5]. In this setting, N nodes are distributed randomly on a rectangular area A of size $A = a \times b$, where $a \leqslant b$. The average node density is denoted by λ. The probability of finding k nodes in A is given by:

$$P(k\ nodes \in A) = e^{\lambda A}\frac{(\lambda A)^k}{k!}. \tag{1}$$

The N nodes establish m random and independently managed networks. Each of these networks has different density. Since the nodes are randomly distributed, they cause interference with each other. The nodes that share the same spectrum can cause intra-channel interference, which can mainly be mitigated by the medium access control mechanism. The nodes that operate in different bands can still cause interference which can be mitigated by supporting dynamic channel allocation and dynamic rate and transmission power adaptation strategies. But this differentiation should be taken loosely since the mitigation strategies applied for an intra-channel interference can be applied for an inter-channel interference and vice versa. The decisions concerning the inter-channel interference are mainly made by the access points, the ones colored black in Fig. 1, while the decision concerning the inter-channel interference are mainly made by individual nodes.

Whereas the decisions concerning dynamic rate and power adaptations can be made by independent agreement between a node and an access point, a decision pertaining to the link layer usually requires cooperation between several nodes. In planned and centrally managed networks, since all nodes belong to the same network, cooperation between the nodes and the access points exists and the nodes abide by the rule of the game [8]. Moreover, in such networks, it is possible to estimate network density and traffic. This knowledge can be useful to apply a suitable set of adaptation strategies for improving the quality of service and the power consumption. For instance, Dong and Dargie demonstrate that the impact of

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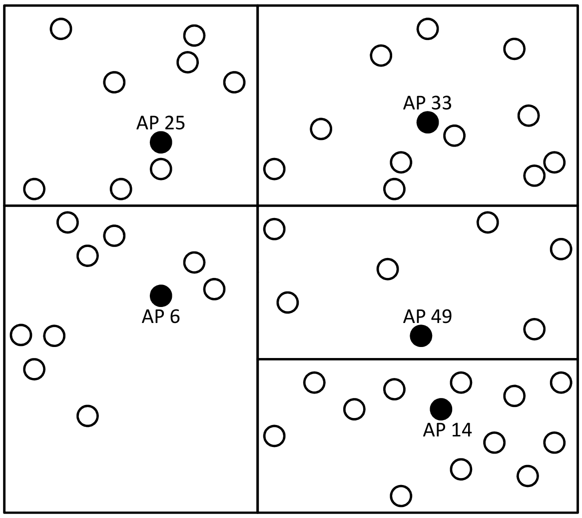

Fig. 1. Network topology.

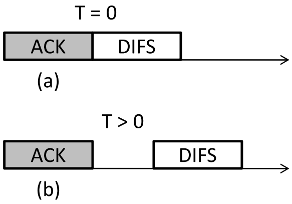

Fig. 2. “Saturated” and “Unsaturated” situation to model collision probability at the link layer.

collision can be reduced once the average number of contending nodes and their transmission and packet generation rate is estimated [6]. Their analytic model enables to examine the gain and cost of control packet overhead at the link layer in a saturated and unsaturated situations.

In a MAC protocol based on the IEEE 802.11 Distributed Coordinate Function (DCF), nodes contend to seize the media by first sensing the channel for a period of time called Distributed Inter-Frame Space (T_{DIFS}). If the channel is free during this period, nodes randomly back-off (with an average back-off time, T_{avg}) before sending a request-to-send (RTS) packet to the intended partner. When the back-off time is over, a RTS will be sent, but a collision may occur if two or more nodes complete their back-off at the same time and simultaneously transmit RTS packets. If a collision occurs, the RTS packets will not be acknowledged, but if there is no collision, the partner node transmits back a clear-to-send (CTS) packet to the transmitter. After the CTS packet, the Data packet will be transmitted and acknowledged.

After the reception of the final ACK frame by the transmitter, the channel becomes free and a new round of competition begins. If nodes contend to cease the medium immediately after the final AKC packet is transmitted, this situation is called “saturated” situation. If, on the other hand, the channel remains unoccupied for a period of time, T: $T > 0$, the situation is called “unsaturated” situation. The two situations are displayed in Fig. 2(a) and (b). The main factors that determine whether a network operates in the saturated or unsaturated situations are the packet arrival rate and the transmission rate. In the former case, the packet arrival rate is equal to or larger than the transmission rate while in the latter case the packet arrival rate is much smaller than the transmission rate.

Dong and Dargie [6] propose an analytic model to estimate the overall collision probability of the medium access control protocol both in the “saturated” and “unsaturated” situations. The model takes the average number of active neighbor nodes, the average back-off time, the control packet overhead, the packet arrival rate and the transmission rate into account to determine when it is efficient to employ control packet overhead. The model can be better explained by dividing the time between two consecutive DIFS periods into two windows (see Fig. 3).

The interval T_1 is related to the transmission rate, R_t, which equals to the summation of the *DIFS* sensing period, T_{DIFS}, the average back-off time, T_{avg}, and the transmission time, T_{trans}:

$$T_1 = T_{DIFS} + T_{avg}\sigma + T_{trans} \tag{2}$$

where σ is the duration of a single slot in the back-off window. T_2 depends on the packet arrival rate and can be expressed as:

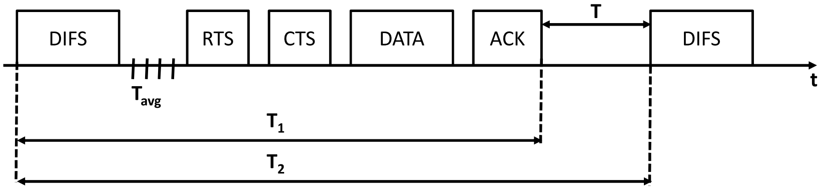

Fig. 3. Modeling contention at the link layer.

Table 1
Simulation setting.

Simulation setting	1	2	3	4
Channels assigned	1, 6, 11	1, 6, 11	1, 3, 6, 8, 11	1
RTS/CTS (on/off)	OFF	ON	OFF	OFF

Table 2
Node density for different applications.

FTP	VoIP	HTTP
60%	20%	20%

$$T_2 = \frac{N_{DATA}}{R_p} \tag{3}$$

where N_{DATA} is the size of the data packet in bytes and R_p is the packet arrival rate. The time interval T can be obtained by subtracting T_1 from T_2:

$$T = \frac{N_{DATA}}{R_S} - T_{DIFS} - T_{avg}\sigma - 3T_{SIFS} - \frac{N_{RTS} + N_{CTS} + N_{DATA} + N_{ACK}}{R_t} \tag{4}$$

where N_{RTS}, N_{CTS} and N_{ACK} are the size of the control packets, RTS, CTS and ACK in bytes, respectively. The model enables nodes and access points to dynamically determine when it is appropriate to switch off the collision avoidance mechanism and when not. One of the aims of this paper is to investigate the usefulness of this model to randomly deployed and independently managed networks.

4. Simulations

4.1. Setting description

We employed the Network Simulator 2 (NS-2) [10] to perform the simulation. There are several implementations of 802.11 standard in NS-2 environment. Ours is based on the enhanced MAC module, Mac/80211ext [4], which enables a more realistic modeling environment. The setting of the simulations is described as follows: 45 mobile nodes randomly associated with 5 access points in an area of $100 \times 100\ \text{m}^2$ as shown in Fig. 1. We consider various network setups to investigate the performance and stability of the collective as well as individual networks: different data traffic used by the mobile nodes (FTP, VoIP and HTTP); dynamic channel allocation mechanisms (single channel, multiple channels; overlapping channels, non-overlapping channels); and the presence and absence of control packet overhead (i.e., the RTS/CTS mechanism is turned on and off). Tables 1 and 2 summarize the simulation settings.

According to Table 1, in settings 1 and 2 the networks occupy partially overlapping channels; in setting 3 the use of non-overlapping channels is better than the previous settings; and in setting 4 all the access points occupy a single channel, to demonstrate the worst case scenario. In order to simulate FTP traffic, the FTP-over-TCP model is used. To provide simulations of VoIP traffic, the constant bit rate (CBR) traffic implementation over UDP is chosen with packet size, $p_s = 80$ Byte and transmission rate, $R_t = 64$ kbps. The HTTP traffic is simulated using the exponential traffic model that is implemented in NS-2.

4.2. Performance

In general, two important observations have been made from the simulation results. Firstly, the simulations confirm that a lack of dynamic channel allocation mechanism dramatically degrades the performance and stability of randomly deployed networks. Secondly, the collision avoidance mechanism, which is effective in dealing with problems related to hidden terminals in IEEE 802.11 networks contributes only marginally here. This is because nodes are distributed in very close proximity and packet collision due to hidden terminals is a rare occurrence. In the following subsection, a more detailed description of the four different settings will be given.

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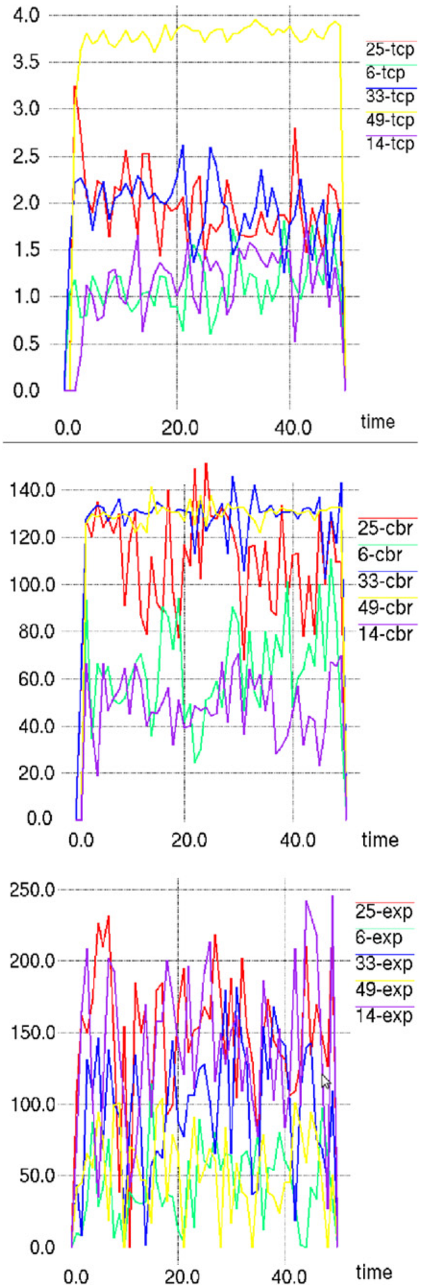

Fig. 4. FTP (above), VoIP (middle) and HTTP (bottom) traffic with the collision avoidance mechanism turned off in a partial dynamic channel allocation setting.

4.2.1. Setting 1 (channels 1, 6, 11; RTS/CTS OFF)

In this setting the networks operate in channels 1, 6, and 11. More specifically, channels 1 and 11 are shared by two of the networks which are not direct neighbors and channel 6 is used by the 5th network, which is towards the center (AP 49) in Fig. 1. The contention avoidance mechanism is turned off. The node density for the different applications is as described in Table 2.

In Fig. 4 the average number of packets transmitted by the three applications - FTP, VoIP, HTTP - is displayed. The performance of the network with the AP 49 is significantly higher (two times better) and more stable compared with the other networks. The remaining networks have a significantly low packet throughput due to an inter-channel interference, but the networks are stable. Interestingly, the collision avoidance mechanism does not significantly affect the FTP traffic (we shall see shortly the comparative traffic throughput with the collision mechanism turned on). The only cost introduced as a result of the absence of the collision avoidance mechanism is latency and jitter in packet transmission, both of which are

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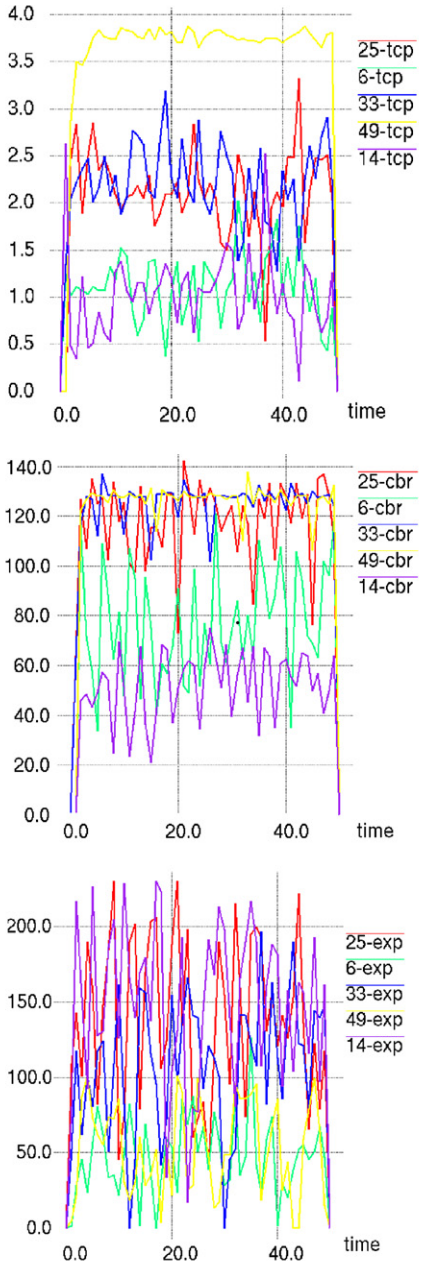

Fig. 5. FTP (above), VoIP (middle) and HTTP (bottom) traffic with the collision avoidance mechanism turned on in a partial dynamic channel allocation setting.

not critical to the FTP applications. For the VoIP, as expected, the throughput of the access point with the non-overlapping channel is relatively high and stable. But all the other networks performed poorly and the fluctuation in transmission volume is conspicuous. The fluctuation in the bursty traffic of the HTTP applications is even worse.

4.2.2. Setting 2 (channels 1, 6, 11; RTS/CTS ON)

This setting is similar to the previous one except for the fact that the collision avoidance mechanism is turned on. Fig. 5 illustrates the impact of collision on the network throughput and stability. As can be seen, the collision avoidance mechanism does not appear to have a profound impact on both. In fact, as far as packet transmission rate is concerned, it is slightly lower than the previous setting due to the additional control packets and the introduction of $3 \times SIFS + DIFS$ interframe spaces for every packet transmitted.

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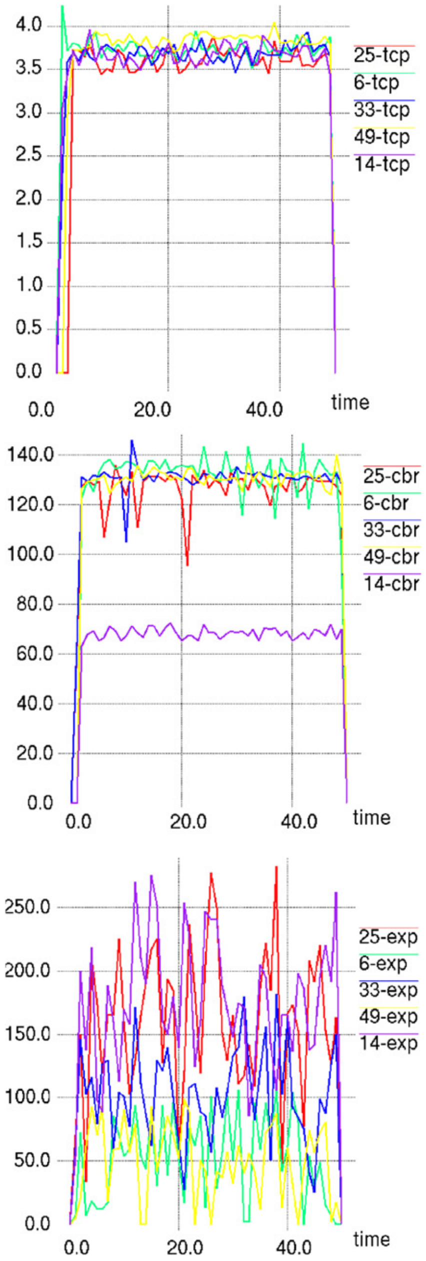

Fig. 6. FTP (above), VoIP (middle) and HTTP (bottom) traffic with the collision avoidance mechanism turned off in an enhanced dynamic channel allocation setting.

4.2.3. *Setting 3 (channels 1, 3, 6, 8, 11; RTS/CTS OFF)*

In this setting, the number of non-overlapping channels is bigger than the previous setting. The collision avoidance mechanism is turned off. The node density for the different applications is as described in Table 2.

The substantial increase in the volume of packets transmitted by the three applications can be observed in Fig. 6. At the top is shown the fluctuation in packet throughput of the FTP application. Obviously, the result is much better than in the previous settings. With the non-overlapping channels, the medium is so efficiently utilized such that the overall performance of all the networks is almost identically good. Furthermore, the collision rate is low. In the middle, the performance of the networks for the VoIP application is displayed. The networks are stable and unaffected by the contention at the link layer. This demonstrates that the significance of using non-overlapping channels in randomly deployed networks is paramount.

4.2.4. *Setting 4 (single channel operation; RTS/CTS OFF)*

In this setting all the networks share a single channel demonstrating the worst case scenario. The collision avoidance mechanism is also turned off. The overall network performance degraded drastically and the networks are unstable. The

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performance of the FTP application is particularly poor. The FTP traffic attempts to utilize the maximum available bandwidth, as a result it resembles the HTTP traffic in the previous settings: bursty and highly unstable. This is due to a high collision rate. Needless to say such networks are unsuitable for the VoIP application. Remarkably, none of the settings are best or worst for the HTTP traffic.

5. Conclusion

We investigated the performance and stability of randomly deployed networks by considering various deployment settings. Several network parameters (contention window, average back-off time, average number of contending nodes) and adaptation strategies (dynamic channel allocation, collision avoidance mechanism) were considered to model the throughput of these networks for different applications (FTP, VoIP and HTTP). Because the networks were not centrally managed, we were particularly interested to investigate the scope and usefulness of some of the adaptation strategies which were employed by well-planned and centrally managed wireless networks when applied to randomly deployed networks.

The simulation was carried out in a NS-2 environment and the following observations were made: Of all the adaptation strategies we employed, dynamic channel allocation greatly improves or affects the performance of the randomly deployed networks. This shows that inter-channel interference is more significant than the intra-channel problem of collision. This observation was further strengthened by the minor contribution of the collision avoidance mechanisms (RTC/CTS) in different deployment settings. For this reason, we recommend to develop more efficient dynamic channel allocation mechanisms for optimal throughput. In most cases, the switching on and off of the control packet mechanism produced little effect. Having said this, the impact of RTS/CTS mechanism should be understood carefully. While it is plausible to conclude that channel allocation plays a more significant role than the collision avoidance mechanism, the NS-2 simulation environment has its own limitations. For example, in our simulation, our network model does not support multi-rate transmission. It has been pointed out elsewhere that unlike in single-rate networks, the impact of RTS/CTS in multi-rate networks is profound [21].

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