Modelling the Impact of User Mobility on the Throughput in Networks of Wireless 802.11 LANs

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***Abstract*— The wireless LAN technology 802.11, also called Wi-Fi, offers high speed wireless Internet access for local area environments. WLANs provide much higher data rates than the mobile 2.5G and 3G networks and are relatively cheap and easy to install and maintain. Consequently, the popularity of WLANs has experienced tremendous growth over the past few years and WLAN technology has become a viable alternative to 2.5/3G mobile networks in providing Internet access in densely populated urban areas.**

The physical characteristics of a WLAN introduce range limitations and unreliable media, dynamic topologies where stations move about, interference from outside sources, and lack of the ability for every device to hear every other device within the WLAN. Due to these limitations service providers are faced with the problem to select and dimension the infrastructure of their WLAN networks caused by difficulties in performance evaluation. The main barrier, however, to the sustained growth of the use of WLANs is their limited capabilities to support user mobility, both in terms of coverage and handover control. Therefore, it is crucial for WLAN service providers to carefully design their networks in terms of the placement of hot spots, explicitly taking into account mobility patterns of the users.

To address this design problem, in this paper we develop a simple model for the performance of WLAN networks, taking into account the limitations in coverage and handover control. The model captures the statistical behaviour of TCP packets at the MAC layer, taking into account the effects of initiation and completion of data transfers due to mobility of the stations when entering or leaving a cell. We develop closed-form expressions for the throughput of TCP flows in IEEE 802.11 WLANs in the presence of multiple classes of customers with different mobility patterns in multiple cells. The expressions are shown to be highly accurate when validated by simulation results.

I. Introduction

The wireless LAN (WLAN) industry is one of the fastest growing segments of the communications industry. These networks address the need to connect to the Internet anytime and anywhere through public hot spots, e.g., at airports, hotels and even parts of cities, that are easy to deploy and offer high data transfer rates in a limited area. A key success factor in the commercial deployment of these services in the public environment is performance.

There are a number of characteristics that are unique to the wireless environment. The physical characteristics of a WLAN introduce range limitations and unreliable media, dynamic topologies where stations move about, interference from outside sources, and lack of the ability for every device to hear every other device within the WLAN. These limitations pose service providers with the problem to select and dimension the infrastructure of their WLAN networks caused by difficulties in performance evaluation. This advocates the need for the development, validation, and analysis of quantitative models to study the performance as experienced by the mobile user.

The performance of WLAN networks is largely dominated by the maximum data rate at the physical layer and the Medium Access Control (MAC) layer protocols. The most widely used WLAN MAC protocol is the Distributed Coordination Function (DCF) as opposed to the Point Coordination Function. The DCF can be best described as a random access scheme based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), where random backoff times are used to manage packet retransmissions when collisions occur.

A. Related literature

A number of papers have studied the performance of the IEEE 802.11 protocol. Most of the earlier work is focused on obtaining the throughput under various network configurations through simulation (see, e.g., Weinmiller et al [1]).

Bianchi [2] developed and analyzed a detailed mathematical performance model of the DCF, which was improved by Wu et al [3]. Both papers have studied the 'saturation throughput' of the IEEE 802.11 MAC layer, which yields an accurate approximation of the WLAN saturation throughput. However, persistent UDP flows instead of TCP flows are studied in their work, resulting in sources always having packets in their queue ready to send. Based on this Markov chain, the situation with non-persistent traffic sources was studied by Litjens et al [4] and Winands [5]. The number of active stations varies dynamically in time according to the initiation and completion of file transfers at random time instants. The authors have proposed an integrated packet/flow level modelling approach.

On the Internet the major part of the traffic is controlled by TCP. TCP also plays an important role in the data transfer over WLAN, and its performance has a direct impact on the

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quality perceived by the end user. There is extensive work on the behaviour of TCP over wired links (see, e.g., Mathis et al [6] and Padhye et al [7]). However, few research results are known about the behaviour over IEEE 802.11 WLANs. Lassila et al [8] proposed an integrated packet/flow level model for estimating the mean transfer time of TCP flows over a fixed capacity (full duplex) bottleneck link. For the packet level they used the results of Kelly [9]. For the flow level a processor sharing type of queueing model was used reflecting TCP's design principle of fair resource sharing.

The ability to support mobility of wireless stations may be the most important aspect for the sustained growth of the use of WLANs. In fact, the recent emergence of enhancements of WLAN technology to include QoS support mechanisms (e.g., 802.11e) and higher data rates and larger coverage areas (e.g., by integrating with WiMax, Wibro, see Wongthavarawat and Ganz [10], and the IEEE 802.16 standard [11]) makes the market potential for WLANs even stronger. For this reason, for the sustained commercial success of WLANs, it is crucial for WLAN service providers to understand the impact of the mobility of the users on the performance of the WLAN network as perceived by the mobile stations. Burmeister et al [12], [13] investigated the performance of mobile stations by simulation. These simulation results show that users achieve the same throughput in individual WLAN cells regardless of their location. The latter also shows that for unsatured sources collisions are neglible and that packet loss rates are very low. The results give some insight in the relationship of network factors and the performance metrics. However, to the best of the authors' knowledge there are no papers providing analytical modelling approaches to the performance of TCP over WLAN as experienced by the mobile stations.

B. Contribution

We present a model for the throughput performance of mobile wireless stations in WLAN networks. The model captures the statistical behaviour of TCP packets at the MAC layer, taking into account the effects due to mobility of stations, i.e., the initiation and completion of data transfers when entering or leaving a cell. We first approximate the aggregated throughput at the packet level of both TCP and the DCF of the 802.11 MAC layer. Then we proceed to develop analytic closed-form expressions for the average throughput of TCP flows in IEEE 802.11 WLAN networks in the presence of multiple classes of customers in multiple cells. We model a single WLAN cell as two queueing servers in tandem. The first server is the setup server, in which the service time is fixed according to the average velocity of the user. The second one is the Internet service server, in which the user's sojourn time is fixed depending on the range of the cell and the average velocity. The WLAN is modelled as a processor sharing (PS) queueing system with a service capacity equal to the aggregated throughput derived in the previous step. NS-2 simulations are used to validate these approximations.

C. Outline

The outline of the paper is as follows. Section II derives the aggregated throughput for each WLAN cell. These results will be used for performance evaluation in Section III. The model will be validated with NS-2 simulations in Section IV. Finally, Section V concludes the paper by summarizing the main results, and mentions some topics for further research.

II. The aggregated TCP throughput model

In our research we focus on the average throughput that the station can achieve during the period inside the AP's coverage. To simplify the complexity, we assume a two-ray ground model for the mobile radio propagation. Hence, when focusing on a single WLAN cell, the AP forms a circular coverage area with a sharp range limit due to the absence of fading or shadowing effects. In this context, we define the throughput as the packet length (excluding the protocol overhead) divided by the time needed to transfer this packet. As known from the protocol's specification, there is some overhead added to the data payload for the protocol usage. More specifically, the overhead consists of the physical layer header, the long PLCP preamble header, the MAC layer header plus the FCS field and the TCP/IP header. Furthermore, not all bits sent by a station can profit from the higher access rates. Both the PLCP preamble and the physical header are transmitted only with 1 Mbps data rate. The basic rate for the control segment RTS and the CTS is 1 Mbps or 2 Mbps. We can now calculate the time T_{P}, necessary to transmit the physical-layer header and the long PLCP preamble,

$$T_{\text{P}} = (L_{\text{PHY}} + L_{\text{PLCP}})/1\ \text{Mbps} = 192\,\mu\text{s}.$$

Furthermore, we denote

- R_{basic} = the RTC/CTS transmission rate,
- R_{data} = the data payload transmission rate,
- DIFS = the time interval Distributed InterFrame Spacing,
- SIFS = the time interval Short InterFrame Spacing,
- L_{RTS} = the length of the RTS control packet,
- L_{CTS} = the length of the CTS control packet,
- L_{MAC} = the overhead added by the MAC layer,
- L_{TCPIP} = the length of the TCP/IP header,
- L_{ACK} = the length of the MAC layer ACK,
- L_{data} = the length of the TCP packets payload,
- T_{slot} = the length of the time slot.

We focus on the Infrastructure BSS, in which usually the RTS/CTS access mechanism is adopted. So here we only conduct the throughput for this access mode.

First, we only consider the raw transmission time for a TCP data packet and a TCP ACK packet, disregarding the backoff procedure (which will be justified later). The WLAN MAC layer is not aware of the content of the data if it receives it from higher OSI layers. Hence, TCP data packets and TCP ACK packets are treated equally. Thus, we can derive the following expression of the time $T_{\text{TCP\_DATA}}$ needed for transmitting of

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the data packet.

$$T_{\text{TCP\_DATA}} = \text{DIFS} + 4\,T_{\text{P}} + 3\,\text{SIFS} + \frac{L_{\text{RTS}} + L_{\text{CTS}} + L_{\text{ACK}}}{R_{\text{basic}}} + \frac{L_{\text{MAC}} + L_{\text{TCPIP}} + L_{\text{data}}}{R_{\text{data}}}.$$

A TCP ACK packet consists just of the TCP/IP header and the MAC layer header, so the time for a TCP ACK transmission can be given by

$$T_{\text{TCP\_ACK}} = T_{\text{TCP\_DATA}} - \frac{L_{\text{data}}}{R_{\text{data}}}.$$

In a WLAN, collisions will occur either when the backoff counters of multiple stations reach zero simultaneously, or in case a so-called hidden station fails to freeze its backoff counter when it cannot sense another station's transmission. In order to get an approximation of the aggregated throughput, we assume that a kind of round robin token is passed between different connections, i.e., the stations obtain the service one by one. This creates a collision free scenario within the AP's coverage. Note that this is not an unrealistic assumption; Burmeister et al [13] show that collisions are neglible when unsaturated sources are considered. Bianchi [2] proves that the average backoff time is half of the contention window size. Thus, the average backoff time $\overline{T}_{\text{backoff}}$ can be given by

$$\overline{T}_{\text{backoff}} = \frac{\text{CW}_{\min}}{2},$$

where $\text{CW}_{\min}$ is the initial Contention Window.

Let N be the random variable denoting the number of stations inside the WLAN cell. In such a case, for any given $\{N = n\}$, the aggregated throughput C is given by n times the throughput of a arbitrary station. Thus,

$$C = n \times \frac{L_{\text{data}}}{n\,(T_{\text{TCP\_DATA}} + T_{\text{TCP\_ACK}} + 2\,\overline{T}_{\text{backoff}}\,T_{\text{slot}})} = \frac{L_{\text{data}}}{T_{\text{TCP\_DATA}} + T_{\text{TCP\_ACK}} + \text{CW}_{\min}\,T_{\text{slot}}}.$$

III. Performance analysis

In this section we are interested in the average throughput of a station when they cross different WLAN cells. We assume that each WLAN cell i has a straight road that is located at a distance d_i from the AP. Let R_i be the coverage of the access point. We assume that there are K classes of customers that can enter the WLAN cell with constant speed v_k, for $k = 1, \ldots, K$.

In theory, the time $T^{(k)}_{\text{total},i}$ that a class k station spends to cross the coverage area of WLAN cell i can be calculated as the distance divided by the velocity of the station, given by

$$T^{(k)}_{\text{total},i} = \frac{2\sqrt{R_i^2 - d_i^2}}{v_k}.$$

Before a station is allowed to send a data message via an AP, it first becomes associated with the AP. The act of becoming associated invokes the association service, which provides the station to AP mapping to the DS. At any given instant, a station may be associated with no more than one AP. Once the association is completed, a station can fully use the DS (via the AP) to communicate.

TABLE I

Setup times for different speeds v

Velocity v (m/s)	Setup Time U (s)	Velocity v (m/s)	Setup Time U (s)
$v \leq 1$	1	$3 < v \leq 5$	5
$1 < v \leq 3$	4	$v > 5$	6

We can model the association server as a queuing system with infinitely many servers. When the mobile station comes inside the range of the AP, the AP server is immediately available for each arriving station to start the association service. Since the service times of the stations are independent, we can model the association server as an $\cdot/G/\infty$ queue. From extensive numerical experiments, we found that the average service time depends on the average velocity v (m/s) of the station. Table I lists the different values for the service times for different speeds v.

We denote the average sojourn time of a mobile station of class k that will stay inside the cell i as $S_i^{(k)}$, which can be calculated by

$$S_i^{(k)} = \frac{2\sqrt{R_i^2 - d_i^2}}{v_k} - U^{(k)},$$

where $U^{(k)}$ is the setup time for a station of class k.

Note that there is no handoff control implemented in the 802.11 protocol versions that are currently available (the 802.11e version supports handoff control, but is not yet widely used in practice today). Hence, when the mobile station moves from one WLAN cell to another, the association process is repeated and after successful association to the next AP the Internet service is resumed. Furthermore, we suppose that cell i receives arrivals of class k stations from outside the system according to a Poisson process with rate $\alpha_i^{(k)}$. A fraction of class k stations that complete their service at cell i are automatically routed to cell j with probability $p_{ij}^{(k)}$. Since there is no call admission control the routed stations are always accepted by the assigned cell.

The system is now modelled as a Markovian open queueing network (i.e., a multi-class open Jackson network). The total average arrival rate $\lambda_i^{(k)}$ of class-k stations to a node i can now be calculated in the usual manner.

$$\lambda_i^{(k)} = \alpha_i^{(k)} + \sum_{j:j\neq i} \lambda_j^{(k)}\,p_{ji}^{(k)}.$$

Note that each cell (say, cell i) in the network behaves as if it were an independent $\cdot/G/\infty$ queue with a Poisson input rate $\lambda_i^{(k)}$ for each class k. In general, the total input will not be a Poisson process. The state variable for a system with M cells consists of the vector $(n_1^{(k)}, \ldots, n_M^{(k)}, k = 1, \ldots, K)$, where $n_i^{(k)}$ is the total number of class-k stations in cell i. The equilibrium probability associated with this state can be denoted by $p(N_1^{(k)} = n_1^{(k)}, \ldots, N_M^{(k)} = n_M^{(k)}, k = 1, \ldots, K)$, where the random variable $N_i^{(k)}$ denotes the total number of class-k stations in cell i. Then we have that

$$(N_i^{(k)} = n_i^{(k)}, i = 1, \ldots, M\,;\, k = 1, \ldots, K) = \prod_{i=1}^{M} \prod_{k=1}^{K} \frac{(\rho_i^{(k)})^{n_i^{(k)}}}{n_i^{(k)}!} e^{-\rho_i^{(k)}},$$

where $\rho_i^{(k)} = \lambda_i^{(k)} \quad S_i^{(k)}$. Then it is easily verified that

$$\Big(\sum_{k=1}^{K} N_i^{(k)} = n_i^{(k)}, i = 1, \ldots, M\Big) = \prod_{i=1}^{M} \frac{(\rho_i)^{n_i}}{n_i!} e^{-\rho_i},$$

where $\rho_i = \sum_{k=1}^{K} \rho_i^{(k)} = \sum_{k=1}^{K} \lambda_i^{(k)} \quad S_i^{(k)}$. Therefore, if we are interested only in the total number of stations of different classes, we may restrict our attention to one infinite server queue only.

The model allows us to study different 802.11 protocols (e.g., 802.11a, 802.11b, or 802.11g) in different cells. Suppose that the aggregated throughput in cell i is C_i. Then, using the processor sharing results, the average throughput TP_i the mobile stations in cell i is easily verified to be

$$\text{TP}_i = \sum_{n_i=0}^{\infty} \quad \Big(\sum_{k=1}^{K} N_i^{(k)} = n_i\Big) \frac{C_i}{n_i + 1} = \frac{C_i}{\rho_i} (1 - e^{-\rho_i}).$$

The total amount of received data $\quad B_i^k$ for class k in cell i is then given by

$$B_i^{(k)} = \quad S_i^{(k)} \,\text{TP}_i = \quad S_i^{(k)} \frac{C_i}{\rho_i} (1 - e^{-\rho_i}).$$

Consequently, for stations of class k that traverse a *given* sequence of cells, say $\pi(1), \ldots, \pi(L)$, the total amount of received data is

$$\sum_{j=1}^{L} \quad B_{\pi(j)}^{(k)} = \sum_{j=1}^{L} \quad S_{\pi(j)}^{(k)} \frac{C_{\pi(j)}}{\rho_{\pi(j)}} (1 - e^{-\rho_{\pi(j)}}),$$

and similarly, the average throughput of these stations is

$$\frac{\sum_{j=1}^{L} \quad B_{\pi(j)}^{(k)}}{\sum_{j=1}^{L} T_{\text{total},\pi(j)}^{(k)}} = \frac{\sum_{j=1}^{L} \quad S_{\pi(j)}^{(k)} \frac{C_{\pi(j)}}{\rho_{\pi(j)}} (1 - e^{-\rho_{\pi(j)}})}{\sum_{j=1}^{L} T_{\text{total},\pi(j)}^{(k)}}.$$

The expressions obtained here are based on the fact that the model possesses a product-form solution. In this context, it is interesting to notice that product-form solutions are preserved for a variety of realistic model extensions, including for example customer classes with fixed deterministic routing schemes and even models where customers may change from class k (with its specific velocity and routing scheme) to class l when moving from one cell to another. This type of model generalizations significantly enhance the flexibility and applicability of the model while product-form solutions can still be obtained. This emphasizes the great potential for the modelling approach presented in this paper.

TABLE II
AVERAGE THROUGHPUT: ANALYSIS VERSUS SIMULATION

Physical Data Rate (Mbps)	Analysis (Mbps)	Simulation (Mbps)	Relative Difference
1	0.6621	0.6912	4.2%
2	1.0971	1.1274	2.6%
11	2.2631	2.2654	0.1%

TABLE III
IEEE 802.11B PARAMETERS

Parameter	Value	Parameter	Value
Radio-propagation	Two-Ray Ground	PHY header	48 bits
Modulation	DSSS	PLCP preamble	144 bits
Carrier Frequency	2412 MHz	MAC header	272 bits
Transmitted Power	24.5 dBm	MAC ACK	112 bits
Data Rate	{1, 2, 11} Mbps	RTS	160 bits
Basic control rate	{1, 2} Mbps	CTS	112 bits
$\text{CW}_{\min}$	31	Time slot	20 μs
SIFS	10 μs	TCP/IP header	320 bits
DIFS	50 μs	TCP data length	8000 bits

IV. NUMERICAL RESULTS

In order to validate the model presented in the previous section, we have compared the theoretical results with NS-2 (version 2.26) simulations. Note that we can, without loss of generality, restrict our attention to a single WLAN cell, since we are dealing with a product-form network.

Table II validates the throughput formula of Section II. It shows the average throughput results of the analytical model versus the simulation results. The relative difference is 4.2% in case of 1 Mbps, and 0.1% in case of 11 Mbps.

The values of the parameters used to obtain the numerical results, for both the analytical model and the simulation, are summarized in Table III. The WLAN parameters are used as the packet level simulations are specified for the Direct Sequence Spread Spectrum (DSSS). The frame sizes are those defined by the 802.11b MAC specification. When we run the simulations with 11 Mbps WLANs, we choose the data rate 11 Mbps and the basic rate 2 Mbps (802.11b multi-rate support). When we run the simulations with 1 Mbps, both the data rate and the basic rate are chosen 1 Mbps. Additionally, to avoid the hidden node problem, we set the carrier-sensing range to be the double of the receiving range.

We next proceed with a scenario with only one class of stations. The stations enter the cell according to a Poisson process with a mean inter-arrival time of 10 seconds. The AP is located 50 m away from the road, and the hearing range of the AP is set to 250 m. The stations drive across the road with constant velocity. In each simulation run, the mobile stations keep the same velocity, however, for different simulation runs, the stations may have different velocities. The setup times are according to the values which are shown in Table I. The results of 13 simulation runs and the curve predicted by the model are drawn in Figure 1, and show that the model is highly accurate with relative errors less than 5%.

Finally, we test the scenario with 2 classes of stations with different velocities. We choose the same system parameters as

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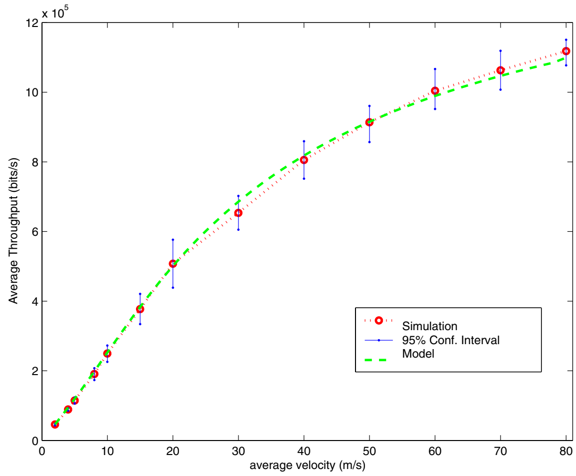

Fig. 1. Average throughput as a function of the velocity

in the previous experiment with the assumption that class 2 station have an inter-arrival time of 20 seconds. The comparison of the analytical results from the model and simulation results are shown in Table IV and Table V. From these two tables we can see that the differences between the simulation results and the model prediction values are all less than 7%. We can conclude that our model can predict the average throughput for different velocities sufficiently accurate.

TABLE IV
AVERAGE THROUGHPUT

Group ID	Speed (m/s)	Throughput Simulation	Throughput Model	Relative Difference
A	2	$3.25\ 10^4$	$3.04\ 10^4$	6.26%
	2	$3.27\ 10^4$		7.02%
B	2	$6.62\ 10^4$	$6.26\ 10^4$	5.36%
	8	$6.66\ 10^4$		6.03%
C	2	$6.90\ 10^4$	$6.73\ 10^4$	2.57%
	10	$6.68\ 10^4$		0.70%
D	2	$7.89\ 10^4$	$7.92\ 10^4$	0.27%
	20	$7.81\ 10^4$		1.34%

TABLE V
TOTAL AMOUNT OF RECEIVED DATA

Group ID	Speed (m/s)	Total-received Simulation	Total-received Model	Relative Difference
A	2	$7.48\ 10^6$	$7.33\ 10^6$	2.01%
	2	$7.55\ 10^6$	$7.33\ 10^6$	2.84%
B	2	$1.49\ 10^7$	$1.51\ 10^7$	1.54%
	8	$3.54\ 10^6$	$3.49\ 10^6$	2.37%
C	2	$1.62\ 10^7$	$1.62\ 10^7$	0.20%
	10	$2.80\ 10^6$	$2.90\ 10^6$	3.34%
D	2	$1.84\ 10^7$	$1.91\ 10^7$	3.47%
	20	$1.51\ 10^6$	$1.46\ 10^6$	3.28%

V. CONCLUSION

We have presented a simple queueing model for the performance analysis of mobile wireless stations in WLAN networks. The model captures the statistical behaviour of TCP packets at the MAC layer, taking into account the effects due to mobility of stations. First, we approximated the aggregated throughput at the packet level of both TCP and the DCF of the 802.11 MAC layer. Then, we studied TCP flows by modelling the WLAN as a processor sharing queueing system with the service capacity equal to the effective WLAN capacity. The model is rich enough to study call admission control problems in WLANs, and to study the optimal placement of APs.

As an interesting topic for future research we mention that the mobile radio channel places fundamental limitations on the performance of wireless communication systems. A more realistic model, taking into account packet loss, could include small-scale fading superimposed on large scale fading. A second enhancement to the model would be to add non-persistent stations. Third, recently the 802.11e version has been proposed to provide QoS support for 802.11 WLANs. Depending on the specifics of this enhancement (e.g., QoS differentiation, handover control), it is an interesting research topic to extend the model proposed in this paper to include these QoS support mechanisms. Finally, currently enhanced WLAN technology improving the data rates and coverage (WiMax, Wibro) are being brought to the market. Extension of the model to integrate the main factors that determine the performance of these new technologies addresses a challenging area for further research.

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