References

1 SMITH, G.H., NOVAK, D., and AHMED, Z.: 'Overcoming chromatic-dispersion effects in fiber-wireless systems incorporating external modulators', *IEEE Trans. Microw. Theory Tech.*, 1997, **45**, (8), pp. 1410–1415

2 DAVIES, B., and CONRADI, J.: 'Hybrid modulator structures for subcarrier and harmonic subcarrier optical single sideband', *IEEE Photonics Technol. Lett.*, 1998, **10**, (4), pp. 600–602

3 HUI, R., *et al.*: '10-Gb/s SCM fiber system using optical SSB modulation', *IEEE Photonics Technol. Lett.*, 2001, **13**, (8), pp. 896–898

4 LOAYSSA, A., BENITO, D., and GARDE, M.J.: 'Single-sideband suppressed-carrier modulation using a single-electrode electrooptic modulator', *IEEE Photonics Technol. Lett.*, 2001, **13**, (8), pp. 869–871

5 DENNIS, M.L., DULING, III I.N., and BURNS, W.K.: 'Inherently bias drift free amplitude modulator', *Electron. Lett.*, 1996, **32**, (6), pp. 547–548

6 GOPALAKRISHNAN, G.K., *et al.*: 'Performance and modeling of broadband $LiNbO_3$ traveling wave optical intensity modulators', *J. Lightwave Technol.*, 1994, **12**, (10), pp. 1807–1819

Throughput analysis of linear backoff scheme in wireless LANs

V. Vitsas

An analytical study is presented of the effectiveness of linear contention window adjustment combined with a long slot duration in the collision avoidance procedures of wireless LAN protocols. A long collision avoidance slot (CAS) duration that includes the beginning of the CTS frame deals with collisions caused by hidden stations. Results indicate that linear backoff minimises empty CASs and reaches a throughput performance very close to maximum. Maximum throughput results obtained by differentiating the throughput equation are compared with similar results in the literature for the IEEE 802.11 protocol.

Introduction: The Infrared Data Association (IrDA) is an industry consortium aiming to develop and promote standards for indoor, low-cost wireless connectivity using the unregulated infrared spectrum [1]. IrDA proposed the Advanced Infrared (AIr) standard for indoor wireless LANs using wide angle infrared ports. The AIr physical layer uses a four-slot pulse position modulation with variable repetition encoding (4PPM/VR) scheme with a base data rate of 4 Mbit/s [2, 3]. The AIr medium access control layer (AIr MAC) co-ordinates access to the infrared medium using carrier sense multiple access with collision avoidance (CSMA/CA) techniques [1]. The AIr MAC provides reserved media access using the request to send/clear to send (RTS/CTS) frame exchange. The AIr MAC defines a long collision avoidance slot (CAS) time duration (σ) that includes the beginning of the responding CTS frame as opposed to the similar IEEE 802.11 protocol which defines a CAS time duration that includes only the beginning of the originating RTS frame. AIr long σ time duration ensures that stations hidden from the transmitter but not from the receiver will hear the CTS during the CAS and will not cause a collision. To cope with delays arising from the long CAS duration, AIr defines linear contention window (CW) adjustment: CW is decreased by 4 after a successful reservation and increased by 4 after a collision. The linear CW adjustment is preferable than the exponential backoff scheme employed by the IEEE 802.11 protocol since the long σ duration, combined with the high number of empty CASs introduced by the exponential backoff scheme, would result in significant delays. To minimise reservation attempts and collision avoidance delays, the AIr MAC allows the transmission of packets per burst (ppb) frames after a successful RTS/CTS frame exchange. The AIr MAC collision avoidance scheme has been studied using simulation techniques in [4]. In this Letter we present studies of the effectiveness of the linear CW adjustment and the long σ duration by developing a mathematical model for the throughput performance of the AIr MAC protocol assuming error-free transmissions and a finite number of contending stations. The key approximation of the mathematical model is the assumption that an RTS frame transmission collides with a constant probability, which is independent of the station's current CW value. A mathematical model based on the same assumption is developed in [5, 6] for the exponential backoff scheme of the IEEE 802.11 protocol.

Analysis: The analytical model considers the saturation throughput for AIr LANs with a fixed number of stations (n) that always have a burst of frames ready for transmission. The AIr MAC Reserved mode sequenced transfer (SDATA frames) is considered. Let $b(t)$ be the stochastic process that represents the number of the remaining CASs a station defers before transmission. Time scale t is slotted; t and $t+1$ represent the beginning of two consecutive CASs. Thus, an increment in the t scale may contain a successful reservation. We use $W = CW_{min}$. Let m be the 'maximum backoff stage' defined as $CW_{max} = W + 4m$ and $W_i = W + 4i$, $i \in (0, m)$, where i is defined as the 'backoff stage'. The AIr standard specifies that $W = 8$, $CW_{max} = 256$ and $m = 62$. Let $s(t)$ be the stochastic process representing the backoff stage $(0, \ldots, m)$ of the station at time t. Based on the key assumption that the collision probability p is constant and independent of the current W_i value, the bidimensional process $\{s(t), b(t)\}$ is modelled by the discrete-time Markov chain shown in Fig. 1.

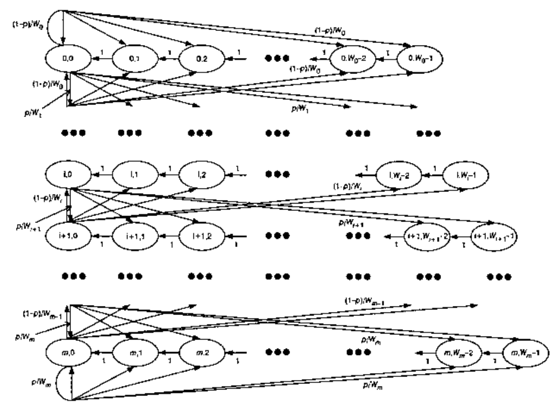

Fig. 1 *Markov chain model for backoff CW*

Let $b_{i,k} = \lim_{t\to\infty} P\{s(t) = i, b(t) = k\}$, $i \in (0, m)$, $k \in (0, W_i - 1)$ be the stationary distribution of the chain. It can be shown that

$$1 = \frac{b_{00}}{2}\left[(W+1)\frac{(1-p)^{m+1} - p^{m+1}}{(1-2p)(1-p)^m} + \frac{4p(1-p)}{(1-2p)^2} \times \left(1 - \frac{p^m(1+m) - p^{m+1}(2m+1)}{(1-p)^{m+1}}\right)\right] \quad (1)$$

The probability τ that a station transmits in a randomly chosen CAS is given by

$$\tau = b_{00}\frac{(1-p)^{m+1} - p^{m+1}}{(1-2p)(1-p)^m} \quad (2)$$

Collision probability p is given by

$$p = 1 - (1-\tau)^{n-1} \quad (3)$$

Equations (1), (2) and (3) form a nonlinear system with the unknowns b_{00}, τ and p that can be solved using numerical methods. The probability P_{sc} that a successful transmission occurs in a given CAS is given by

$$P_{sc} = n\tau(1-\tau)^{n-1} \quad (4)$$

Throughput efficiency S is given by

$$S = \frac{P_{sc} l\, ppb/C}{P_{sc}T_s + \sigma - P_{sc}\sigma} \quad (5)$$

where l is the payload data length, C is the data rate and T_s is the duration of a successful reservation. Calculated throughput efficiency from (5) is compared with AIr simulation results and is proven extremely accurate for various network scenarios. Our AIr simulator is developed using the OPNET™ modeller.

Maximum throughput: The optimum CW (W_{opt}) value that contenting stations must implement for maximum throughput for a LAN with n transmitting stations can be found by employing the analytical model for $m = 0$. By setting the first derivative of the throughput equation against τ equal to zero, we derive that $\tau_{opt} = 1/n$ and

$$W_{opt} = 2n - 1 \tag{6}$$

$$S_{\max} = \frac{l\,ppb/C}{T_s - \sigma + \sigma(n/(n-1))^{n-1}} \tag{7}$$

Equation (7) shows that maximum throughput depends on network size. However, when n gets large, maximum throughput reaches a steady value. This conclusion is slightly different to the expressed conclusion in [6] that maximum throughput for the IEEE 802.11 protocol is independent of n although the exponential backoff scheme of the IEEE 802.11 protocol coincides with the AIr linear backoff scheme when no CW adjustment ($m = 0$) is allowed and CW is tuned to the optimum value W_{opt}. Different conclusions arise from the approximations presented in [6] for calculating maximum throughput for the general case where an RTS collision lasts several CAS time periods σ, as in the 802.11 protocol. AIr maximum throughput analysis is accurate and does not include any approximations by taking advantage of the fact that an RTS collision lasts exactly one slot duration in the AIr protocol. Fig. 2 shows throughput efficiency against network size for fixed CW values and focuses on maximum AIr throughput (note that the y-axis ranges from 0.75 to 0.87). It also plots AIr maximum throughput ($S_{\max}$) using (7) and the approximated maximum throughput S_{appr} calculated using the analysis and the approximations presented in [6] for the AIr collision avoidance parameter values. The Figure shows that the approximations presented in [6] result in a lower calculated maximum throughput performance when RTS collisions last exactly one CAS duration, as in the AIr protocol.

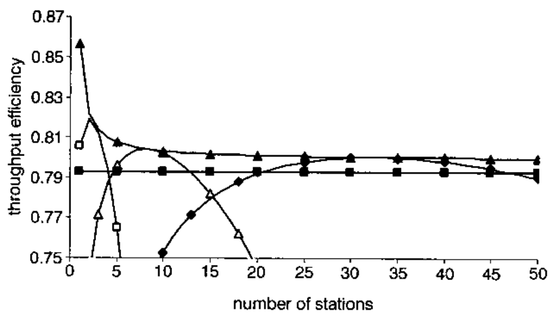

Fig. 2 *Throughput efficiency against n for fixed CW size, SDATA frames*
$l = 16$ Kbits, ppb $= 4$, $C = 4$ Mbit/s
□ CW (slots) = 4
△ CW (slots) = 16
◆ CW (slots) = 64
▲ maximum $S_{\max}$
■ maximum S_{appr}

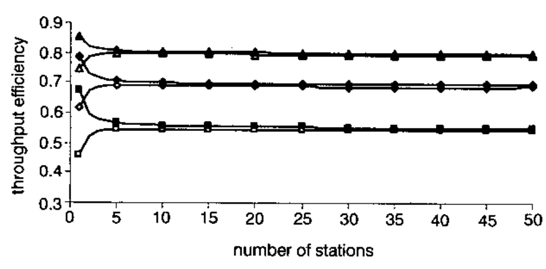

Fig. 3 *Throughput efficiency against n, SDATA frames*
$l = 16$ Kbits, $W = 8$, $m = 62$, $C = 4$ Mbit/s
□ ppb = 1
◇ ppb = 2
△ ppb = 4
■ ppb = 1, $S_{\max}$
◆ ppb = 2, $S_{\max}$
▲ ppb = 4, $S_{\max}$

The effectiveness of the linear backoff adjustment scheme is explored in Fig. 3, which compares maximum ($S_{\max}$) with AIr throughput efficiency (S) for different ppb values. The linear backoff scheme performs effectively as AIr throughput is very close to maximum for $n > 5$; significant differences are observed only for small networks. In this case, the $CW_{\min}$ value of 8 is larger than the W_{opt} value calculated by (6) and the increased number of empty CASs results in significant throughput degradation.

Conclusions: This Letter studies the effectiveness of linear backoff adjustment combined with a long collision avoidance slot duration in CSMA/CA protocols. Analytical results indicate that linear backoff reaches a throughput performance very close to maximum. Considering that this scheme also deals with collisions caused by hidden stations, it provides an efficient alternative for collision avoidance procedures.

18 September 2002
Electronics Letters Online No: 20030067
DOI: 10.1049/el:20030067

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References

1 WILLIAMS, S.: 'IrDA: past, present and future', *IEEE Pers. Commun.*, 2000, 7, (1), pp. 11–19
2 GFELLER, F., and HIRT, W.: 'Advanced Infrared (AIr): physical layer for reliable transmission and medium access'. Proc. 2000 Int. Zurich Seminar on Broadband Communications, Zurich, Switzerland, 2000, pp. 77–84
3 GHASSEMLOOY, Z., HAYES, A.R., SEED, N.L., and KALUARACHCHI, E.D.: 'Digital pulse interval modulation for optical communications', *IEEE Commun. Mag.*, 1998, **35**, (12), pp. 95–99
4 BARKER, P., and BOUCOUVALAS, A.C.: 'A simulation model of the Advanced Infrared (AIr) MAC protocol using OPNET'. 2nd Int. Symp. on Communication Systems, Networks and DSP, CSNDSP 2000, Bournemouth, UK, pp. 153–156
5 BIANCHI, G.: 'IEEE 802.11: saturation throughput analysis', *IEEE Commun. Lett.*, 1998, **2**, (12), pp. 318–320
6 BIANCHI, G.: 'Performance analysis of the IEEE 802.11 distributed coordination function', *IEEE JSAC Wirel. Ser.*, 2000, **18**, (3)

1.3 µm GaInNAs optically-pumped vertical cavity semiconductor optical amplifier

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A GaInNAs/GaAs vertical cavity semiconductor optical amplifier (VCSOA) is reported. This is believed to be the first monolithic VCSOA operating at 1.3 µm. Under continuous-wave optical pumping in a singlemode fibre coupled format, gain figures of up to 17.7 dB were achieved. Amplification with 12 GHz bandwidth was obtained at 12.8 dB peak gain.

Recently, considerable attention has been devoted to the development of vertical cavity semiconductor optical amplifiers (VCSOAs), for applications including optical interconnects, optical switching and wavelength-selective pre-amplifiers. This geometry of a semiconductor optical amplifier offers advantages common to VCSEL technology, to which it is closely related, including high coupling efficiency to optical fibre, low noise figure, polarisation insensitivity, and the facility for producing high-density, two-dimensional arrays. Reports to date on VCSOAs at 1.3 µm [1–3] have focused on wafer fusion technology, to produce hybrid structures with GaAs-based distributed Bragg reflectors (DBRs) and InGaAsP/InP multi-quantum well active regions. These structures were optically-pumped through the back GaAs substrate in a free-space coupled arrangement. Here, we report a monolithic VCSOA at 1.3 µm based on a single-step-growth GaInNAs/GaAs structure, with self-aligned, butt-coupled front-pumping using one singlemode fibre to couple-in 980 nm pump and 1300 nm signal light, and to couple-out the amplified 1.3 µm signal. Continuous-wave fibre-to-fibre gains of up