Performance of the R^3T Random-Access OCDMA Protocol in Noisy Environment

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***Abstract*—The effect of both shot noise and thermal noise on the performance of the optical code-division multiple-access (OCDMA) round robin receiver/transmitter (R^3T) protocol is examined. Moreover, the impact of dispersion is studied. Several performance measures, namely, the throughput, the protocol efficiency, and the average packet delay are evaluated. Our results reveal that the R^3T is immune against both thermal and shot noise, and that the effect of dispersion is minor. We found out that there are optimum values for the laser power to compensate for this degradation.**

***Index Terms*—Chip-level receivers, dispersion, optical code-division multiple-access (OCDMA) networks, OCDMA protocols, shot noise, thermal noise.**

I. Introduction

NOWADAYS, as more and more users are attracted by data networks, and as their usage patterns evolve to include more and more bandwidth-intensive networking applications such as data browsing on the Internet, java applications, video conferencing, etc., there emerges an acute need for high-bandwidth transport network facilities, which are much beyond those that current high-speed networks can provide. The optical code-division multiple-access (OCDMA), which constitutes the infrastructure of the next-generation access networks [1]–[9], is the one that gives the highest system resources utilization. This is due to the extra-high bandwidth offered by optical links and optical signal processing speed bestowed by the optical components.

Most efforts in the area of OCDMA have been concentrated on the physical layer [1], [2]. The performance analysis of the slotted and unslotted fiber optic CDMA has been studied in [3] and [4], respectively. Two protocols with and without pretransmission coordination have been proposed for slotted OCDMA packet networks in [5]. However, the effect of multipacket messages, connection establishment, and corrupted packets have not been considered. Recently, Shalaby [6] has developed a new protocol called round robin receiver/transmitter (R^3T) protocol that has solved some of the aforementioned problems. The R^3T protocol is based on a go-back n automatic repeat request (ARQ), that is when a packet gets corrupted, the transmitter retransmits it and all subsequent packets. This scenario gives good performance for only low-population networks. Considering only retransmission of corrupted packets, a selective reject ARQ has been adopted in [7], yielding better performance in larger networks.

Shalaby [6] has focused his analysis only on the effect of multiple-access interference (MAI) and neglected all other sources of noise, which is not the case in a practical situation. Our goal in this paper is to add the effect of both shot noise and thermal noise separately to the MAI, then to study the performance of the R^3T protocol in that noisy environment, and to compare our results with [6]. Furthermore, we study the impact of modal dispersion and chromatic dispersion on the R^3T protocol. Multimode fiber-based LANs are considered in that analysis. The rest of this paper is organized as follows. Section II is devoted to a basic description of the system architecture. A mathematical model and a basic description of the state diagram of the proposed R^3T protocol is outlined in Section III, where a derivation of the packet success probability for shot-noise-limited and thermal-noise-limited cases is given and compared with the ideal one (considering only the effect of MAI). The effect of dispersion is also included. Section IV is maintained for the simulation results, and is followed by the conclusions.

II. System Architecture

A. OCDMA Physical Layer

The physical topology of our OCDMA network is a simple passive broadcast star network connecting N users, as in [5] and [6]. A set of optical orthogonal codes (OOCs) with cardinality $|C|$ that depends on the code weight w, code length L, and both the autocorrelation and cross-correlation constraints λ_a and λ_c, respectively, is used as the users signature sequences. Traditionally,

$$\lambda_a = \lambda_c = 1 \Rightarrow |C| = \left\lfloor \frac{L-1}{w(w-1)} \right\rfloor \tag{1}$$

where $\lfloor x \rfloor$ denotes the largest integer not greater than x

Due to the bursty nature of the traffic, normally, we have $N > |C|$, and users are assigned to OOCs according to one of the two protocols proposed in [5]. Furthermore, the code is randomly cyclic shifted around itself once assigned for interference control

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purposes. Chip-level receivers are used because of their high ability to overcome the effect of MAI. The complete model for this receiver can be found in [8]. Assuming that there are $r \in \{1, 2, \ldots, N\}$ active users, we define $k \in \{0, 1, 2, \ldots, r-1\}$, such that $k = \sum_{i=1}^{w} k_i$, and $m \in \{0, 1, \ldots, r-1-k\}$ as the number of users that interfere with the desired user at exactly one chip and w chips, respectively, and k_i denotes the number of users that interfere with the desired user at weighted chip i. Assuming a packet that is composed of K bits, the conditional packet success probability for chip-level receiver is expressed as follows:

$$P_S(r/m, \bar{k}) = [P_{\rm bc}(m, \bar{k})]^K \tag{2}$$

where $\bar{k} = \{k_1, k_2, \ldots, k_w\}$ is the interference vector and $P_{\rm bc}(m, \bar{k})$ is the bit correct probability. The packet success probability is, thus, given by

$$\begin{aligned} P_S(r) = &\sum_{k=0}^{r-1}\sum_{m=0}^{r-1-k} \frac{(r-1)!}{k!m!(r-1-m-k)!} \\ &\times p_1^k p_w^m (1-p_1-p_w)^{r-1-m-k} \\ &\times \sum_{k_1}, k_2, \ldots, k_w : k_1 + \cdots + k_w \\ = &\, k \frac{k!}{k_1! \cdots k_w!} \left(\frac{1}{w}\right)^k [P_{\rm bc}(m, \bar{k})]^K. \end{aligned} \tag{3}$$

Here, p_1 and p_w, respectively, denote the probability of 1 and w chip interferences between two users [6]

$$p_w = \frac{1}{L}\frac{1}{|C|} = \frac{1}{L}\left\lfloor \frac{L-1}{w(w-1)} \right\rfloor^{-1}, \quad p_1 = \frac{w^2}{L} - w p_w. \tag{4}$$

The bit correct probability of the chip-level receiver considering only the effect of the MAI has been derived in [5] as

$$\begin{aligned} P_{\rm bc}(m, \bar{k}) = &\frac{1}{2} + \frac{1}{2^{m+1}} \\ &\times \left(\sum_{i=1}^{w} \frac{1}{2^{k_i}} - \sum_{i=1}^{w-1}\sum_{j=i+1}^{w} \frac{1}{2^{k_i+k_j}} + \cdots + (-1)^{w-1}\frac{1}{2^k} \right). \end{aligned} \tag{5}$$

B. OCDMA Protocol

In the R^3T protocol, many assumptions were imposed [6]. Briefly, time is slotted with slot size T_s and a message is composed of ℓ packets. A packet must fit in only one time slot, i.e., $T_s = KLT_c$, where T_c is the chip duration. Each node has a single buffer to store only one message, connection requests and acknowledgments are exchanged between stations; finally, the ARQ used is a go-back n protocol, and the two-way propagation time is assumed to be equal to t time slots.

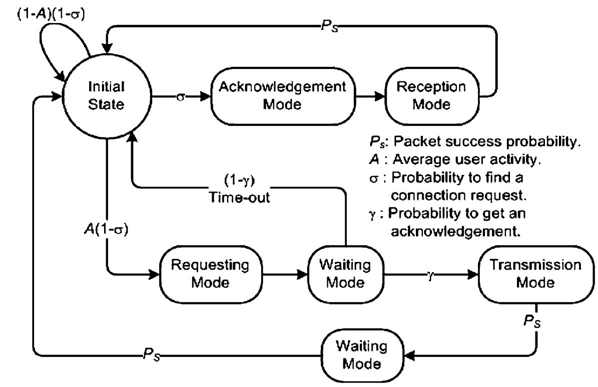

Fig. 1. Simplified state diagram of R^3T protocol.

III. Mathematical Model and Analysis

A. Simplified State Diagram of R^3T Protocol

A simplified state diagram for the R^3T OCDMA protocol is shown in Fig. 1. A user in the initial state scans across the codes in a round robin method. When a connection request is found, the terminal proceeds to send an acknowledgment (ACK), and enters the reception mode. When all packets are received successfully, the user returns to the initial state. The station moves to the requesting mode from the initial state if no requests are found and if there is a message arrival. After sending a connection request, the station enters a waiting mode till it receives an ACK. If timed out (after τ time slots), the user returns to the initial state, otherwise he starts transmission. After transmission, the station waits to collect the ACKs of the last packets sent, and then returns to the rest state. The station remains idle if there are no arrivals and no requests are found.

Because of the complexity of the mathematical model given earlier, in Shalaby [6] used the equilibrium point analysis (EPA) to measure the protocol performance. The throughput $\beta(N, A, t, \tau, \ell)$ is defined as the number of successful received packets per slot, and is given by [6]

$$\beta(N, A, t, \tau, \ell) = \frac{P_S(r_o)\ell r_0}{\ell + (1 - P_S(r_o))(t \wedge \ell - 1)(\ell - t \wedge \ell/2)} \tag{6}$$

where $t \wedge \ell$ is defined as $\min\{t, \ell\}$ and r_o denotes the number of transmitting users in a given slot, and is given by the solution of the following equation [6]:

$$\begin{aligned} &N[\ell + (1 - P_S(r_o))(t \wedge \ell - 1)(\ell - t \wedge \ell/2)] \\ &= r_o \Big[2t\ell(1 - P_S(r_o)) + (2t + 2\ell - 1)P_S(r_o) \\ &\quad + \frac{P_S(r_o)}{\sigma} + A(t-1)\frac{1-\sigma}{\sigma}P_S(r_o) \\ &\quad + \left\{1 - \left[1 - \frac{\sigma}{A(1-\sigma)}\right]^{1/\tau}\right\}^{-1} P_S(r_o)\Big]. \end{aligned} \tag{7}$$

The protocol efficiency η and the average packet delay D (measured in slots) are expressed as follows:

$$\eta = \frac{\beta(N, A, t, \tau, \ell)}{N/2,} \qquad D = \frac{NA}{\beta(N, A, t, \tau, \ell)}. \tag{8}$$

Considering the effect of only MAI, we can write the packet success probability by substituting (5) in (3) as follows:

$$\begin{aligned} P_S(r) = &\sum_{k=0}^{r-1} \sum_{m=0}^{r-1-k} \frac{(r-1)!}{k!m!(r-1-m-k)!} \\ &\times p_1^k p_w^m (1-p_1-p_w)^{r-1-m-k} \\ &\sum_{\cdot k_1, k_2, \cdots, k_w : k_1+\cdots+k_w=k} \frac{k!}{k_1! \cdots k_w!} \left(\frac{1}{w}\right)^k \\ &\cdot \left[\frac{1}{2} + \frac{1}{2^{m+1}} \left(\sum_{i=1}^{w} \frac{1}{2^{k_i}} - \sum_{i=1}^{w-1} \sum_{j=i+1}^{w} \frac{1}{2^{k_i+k_j}} \right.\right. \\ &\left.\left. + \cdots + (-1)^{w-1} \frac{1}{2^k} \right)\right]^K . \end{aligned} \tag{9}$$

Now, we are going to study the performance of the R^3T protocol taking into account the effect of both shot and thermal noises, then the dispersion effect will be discussed. The only change in the throughput equation will be in the evaluation of the packet success probability, or more precisely, the bit correct probability.

B. Poisson Shot-Noise-Limited Photodetectors

Assuming that the receiver's photodiode is shot noise limited, the bit correct probability can be found in [5]. We have modified its form using the exclusion–inclusion principle to get this general form, which is more simple and suitable for simulations.

$$\begin{aligned} P_{\rm bc}(m, \bar{k}) = &\frac{1}{2} - \frac{1}{2} \sum_{b=0}^{1} (-1)^b \sum_{i=1}^{w} (-1)^i \binom{w}{i} e^{-Qbi} \\ &\times \left(\frac{1}{2} + \frac{1}{2} e^{-Qi}\right)^m \left(\frac{1}{2} + \frac{1}{2} e^{-Q}\right)^{\sum_{j=1}^{i} k_j} . \end{aligned} \tag{10}$$

Here, $b \in \{0, 1\}$ is the data bit and Q denotes the average photon count per chip pulse that is related to the average photons per bit μ by $Q = 2\mu/w$.

C. Thermal-Noise-Limited Case

In our model, we assume that the decision variable Y_j for the chip-level receiver that indicates the photon count per marked chip positions $j \in x = \{1, 2, \ldots, w\}$ has a Gaussian distribution, and the decision threshold θ will have to be optimized [9]. Considering u users out of m users interfering in w chips and v_j users out of k_j users making interference at the weighted chip j, the conditional mean and variance $m_{\rm bj}$ and $\sigma_{\rm bj}^2$, respectively, are expressed as follows:

$$m_{\rm bj} = G\left((u + b + v_j)\, Q \; + Q_d\right), \qquad \sigma_{\rm bj}^2 = FGm_{\rm bj} + \; \sigma_n^2. \tag{11}$$

Here, G denotes the average APD gain, Q and Q_d are the average number of absorbed photons per received single-user pulse and the photon count due to the APD dark current within a chip interval T_c, respectively, and are given by [9]

$$Q = \frac{RP_{\rm av}T}{ew}, \quad Q_d = \frac{I_d T_c}{e} \tag{12}$$

where $P_{\rm av}$ is the received average peak laser power (of a single user), T is the bit duration, R is the APD responsivity at unity gain, I_d is the APD dark current, and $e = 1.6 \times 10^{-19}$C is the magnitude of the electron charge. The variance of the thermal noise within a chip interval σ_n^2 is as follows:

$$\sigma_n^2 = \frac{2K_B T^o}{e^2 R_L} T_c \tag{13}$$

where $K_B = 1.38 \times 10^{-23}$J/K is Boltzmann's constant, T^o is the receiver noise temperature, and R_L is the receiver load resistor. Defining $k_{\rm eff}$ as the APD effective ionization ratio, the APD excess noise factor F can be written as

$$F = k_{\rm eff} G + \left(2 - \frac{1}{G}\right)(1 - k_{\rm eff})\,. \tag{14}$$

We start by deriving the corresponding bit correct probability as follows:

$$\begin{aligned} &P_{\rm bc}(m, \bar{k}) \\ &= \frac{1}{2} \Pr\{\text{a bit success} \,|\, m,\ k,\ 1 \text{ was sent}\} \\ &\quad + \frac{1}{2} \Pr\{\text{a bit success} \,|\, m,\ k,\ 0 \text{ was sent}\} \\ &= \frac{1}{2} \Pr\{\ Y_j \geq \theta \text{ for all } j \in x \,|\, m, \bar{k},\ 1 \text{ was sent}\} \\ &\quad + \frac{1}{2} \Pr\{Y_j < \ \theta \text{ for some } j \ \in \ x \,|\, m,\ \bar{k},\ 0 \text{ was sent}\}. \end{aligned} \tag{15}$$

Using the inclusion–exclusion property yields

$$\begin{aligned} P_{\rm bc}(m, \bar{k}) = &\frac{1}{2} + \frac{1}{2} \sum_{b=0}^{1} (-1)^b \\ &\times \Pr\{Y_j < \ \theta \text{ for some } j \ \in \ x \,|\, m,\ \bar{k},\ b\} \\ = &\frac{1}{2} - \frac{1}{2} \sum_{b=0}^{1} (-1)^b \sum_{i=1}^{w} (-1)^i \binom{w}{i} \\ &\times \Pr\{Y_1, Y_2, \ldots, Y_j < \theta \,|\, m, \bar{k}, b\}. \end{aligned} \tag{16}$$

The last probabilities can be expressed as follows:

$$\begin{aligned} &\Pr\{Y_1, Y_2, \ldots, Y_j < \theta \,|\, m,\ \bar{k},\ b\} \\ &= \sum_{u=0}^{m} \binom{m}{u} \left(\frac{1}{2}\right)^m \sum_{v_1=0}^{k_1} \binom{k_1}{v_1} \left(\frac{1}{2}\right)^{k_1} \\ &\quad \times \sum_{v_2=0}^{k_2} \binom{k_2}{v_2} \left(\frac{1}{2}\right)^{k_2} \cdots \sum_{v_i=0}^{k_i} \binom{k_i}{v_i} \left(\frac{1}{2}\right)^{k_i} \end{aligned}$$

$$\Pr\{Y_1 < \theta | u, v_1, b\} \Pr\{Y_2 < \theta \,|\, u, v_2, b\} \cdots \Pr\{Y_i < \theta | u, v_i, b\} = \sum_{u=0}^{m} \binom{u}{m} \left(\frac{1}{2}\right)^m \prod_{j=1}^{i} \sum_{v_j=0}^{k_j} \binom{k_j}{v_j} \left(\frac{1}{2}\right)^{k_j} Q\left(\frac{m_{\mathrm{bj}} - \theta}{\sigma_{\mathrm{bj}}}\right) \tag{17}$$

where $Q(x)$ is the normalized Gaussian tail probability

$$Q(x) = \frac{1}{\sqrt{2\Pi}} \int_x^{\infty} e^{-s^2/2} ds. \tag{18}$$

Combining last equations, we can get an expression for the bit correct probability as follows:

$$P_{\mathrm{bc}}(m, k, b) = \frac{1}{2} - \frac{1}{2} \sum_{b=0}^{1} (-1)^b \sum_{i=1}^{w} (-1)^i \binom{i}{w} \times \sum_{u=o}^{m} \binom{m}{u} \left(\frac{1}{2}\right)^u \left(\frac{1}{2}\right)^{m-u} \times \prod_{j=1}^{i} \sum_{v_j=0}^{k_j} \binom{k_j}{v_j} \left(\frac{1}{2}\right)^{k_j} Q\left(\frac{m_{\mathrm{bj}} - \theta}{\sigma_{\mathrm{bj}}}\right). \tag{19}$$

D. Dispersion Effect

One of the limitations in optical communication systems is the dispersion effect, which results in temporal widening of optical pulses, and therefore, limits the user bit rate. Modal dispersion and chromatic dispersion are the two mechanisms causing pulse spreading when selecting a graded index multimode fiber that is already installed in most of the network infrastructures [10].

Considering first modal dispersion, which is the main part that contributes in dispersion, the pulse spreading is [10]

$$\Delta t_{\mathrm{modal}} = \frac{(\mathrm{NA})^4}{32 c n_1^3} z \tag{20}$$

where NA denotes the numerical aperture of the fiber, n_1 is the core refractive index, $c = 3 \times 10^8$ m/s is the speed of light in free space, and z is the fiber length, or more precisely, the interstation distance, and is given by

$$z = \frac{vt}{2} \times T_s \tag{21}$$

here, v denotes the velocity of light in fiber and is related to its refractive index n_1.

Now, we consider the chromatic dispersion, which is the combination of material dispersion and waveguide dispersion.

We define the chromatic dispersion parameter as follows [10]:

$$D(\lambda) = \frac{S_o}{4} \times \left[\lambda - \frac{\lambda_o^4}{\lambda^3}\right] \tag{22}$$

where λ is the operating wavelength, λ_o is the zero dispersion wavelength, and S_o is the zero dispersion slope. Let $\Delta\lambda$ be the spectral width of the used light source. The pulse spreading can be expressed by

$$\Delta t_{\mathrm{chrom}} = D(\lambda) \Delta\lambda z. \tag{23}$$

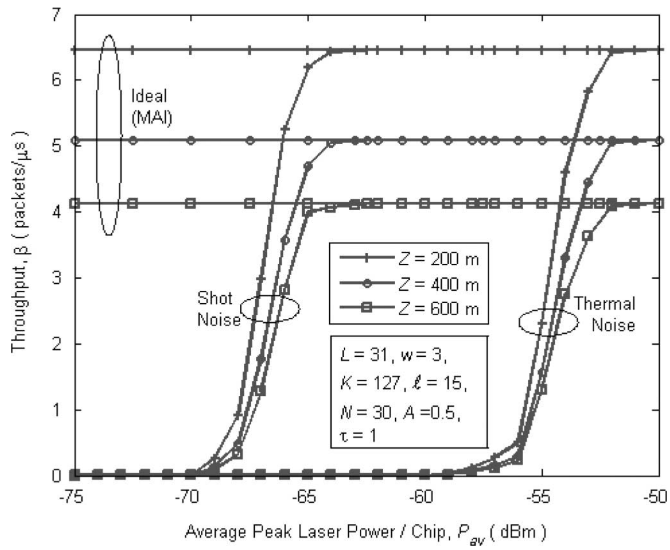

Fig. 2. Throughput vs. average-peak laser power.

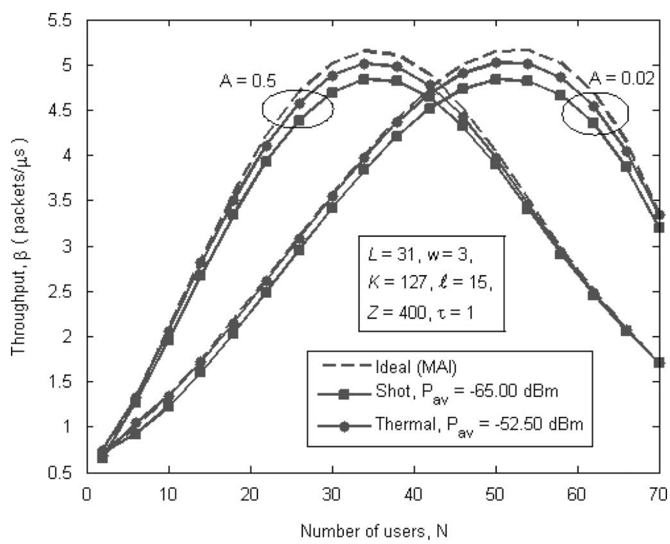

Fig. 3. Throughput vs. number of users for different activities.

The effect of dispersion can be modeled by simply extending the slot duration to T_s'.

$$T_s' = KL\sqrt{T_c^2 + \Delta t_{\mathrm{modal}}^2 + \Delta t_{\mathrm{chrom}}^2}\, s. \tag{24}$$

This accounts for a guard period added to each chip in order to overcome problems with intersymbol interference.

IV. Numerical Results

The packet success probability, the steady-state system throughput, the average packet delay, and the protocol efficiency derived as before have been evaluated for chip-level receivers taking into account the effect of MAI on the protocol's performance. The performance degradation when considering shot and thermal noises are then included. Our results are plotted in Figs. 2–6. Most of the simulation parameters are listed in

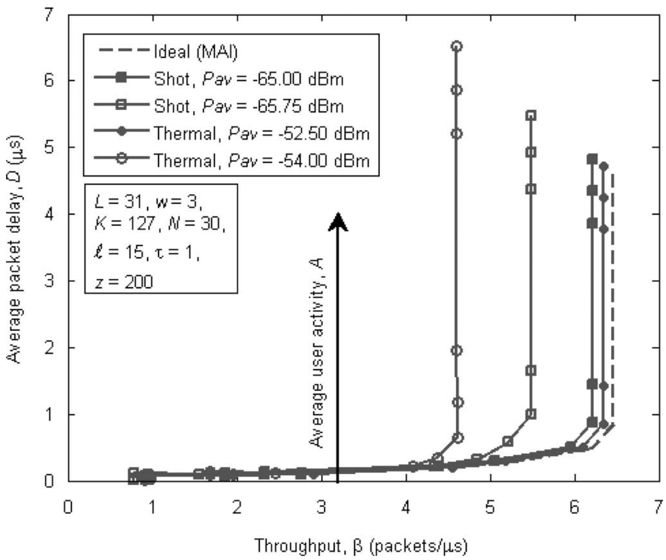

Fig. 4. Packet delay vs. system throughput.

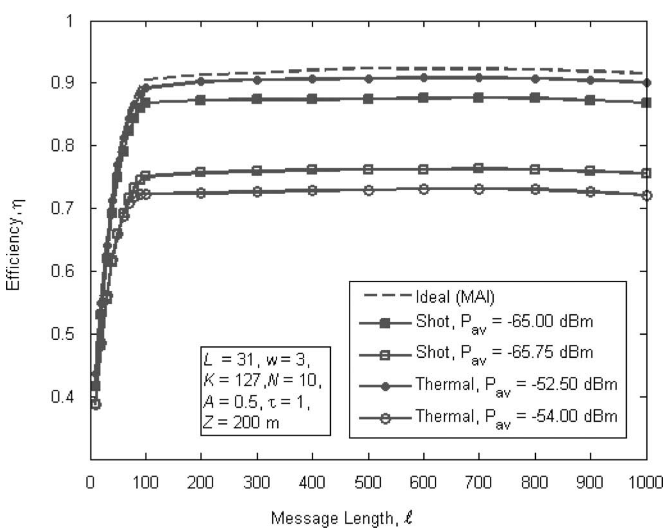

Fig. 5. Efficiency vs. message length for different power levels.

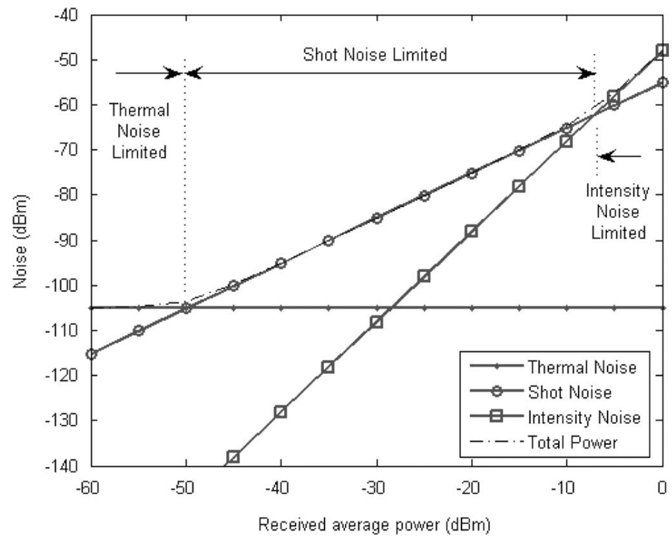

Fig. 6. Noise power vs. received power for different noise sources.

TABLE I
TYPICAL VALUES OF SIMULATION PARAMETERS

CDMA Encoding Parameters		**Photo-detector**	
Data	*OOCs*	*APD*	
$\ell = 15$ packets	$L = 31$	$R = 0.84$ A/W	$I_d = 1$ nA
$K = 127$ bits	$w = 3$	$G = 100$	$k_{eff} = 0.02$
	$\lambda_a = \lambda_c = 1$	$T^o = 300$ K	$R_L = 50\,\Omega$

Table I. A time-out duration of $\tau = 1$ slot is held constant, and a time slot of $T_s = 1\,\mu$s are imposed in all figures but Fig. 6. Practical values of interstation distances $z \in \{200, 400, 600\}$m have been selected.

In Fig. 2, the throughput has been plotted against the average peak laser power for different interstation distances. General trends of the curves can be noticed. The throughput falls down as the interstation distance increases as in [6]. By increasing the average received laser power up to -63 dBm (shot noise) or -51 dBm (thermal noise), and regardless the interstation distance and other network parameters, the receiver can tolerate the effect of noise. The independence on all the network parameters can be argued by inspecting (6)–(8). It can be noticed that the only changes in equations when considering the effect of noise will be the value of the packet success probability. Therefore, by simply increasing the power, we can get the same packet success probability as the ideal case (MAI only), and therefore, the same system performance.

In Fig. 3, the throughput has been plotted versus the number of users for different arrival rates. Similar trends of the curves can be noticed. There is always an optimum value of N that maximizes the throughput as in [6]; also, the position of this peak is shifted when changing the average activity so as to maintain approximately a constant traffic in the network. It can also be noticed that, for large number of users, the effect of MAI is dominant.

Fig. 4 depicts the relation between the average packet delay and the throughput. It has been plotted for different values of laser power. As inspected, it can be seen that there is a tradeoff between throughput and delay. As the average user activity increases, the throughput saturates [6] and the delay grows rapidly. The behavior of the system under the effect of noise is similar to the one shown in Fig. 2 for an interstation distance of 200 m.

The protocol efficiency versus the message length ℓ for different power levels is shown in Fig. 5. As proved in [6], for a given number of stations, the protocol efficiency can reach 95% with suitable selection of code weight, code length, and furthermore, at a certain average peak laser power. The effect of changing the power can also be explained by referring to the previous results.

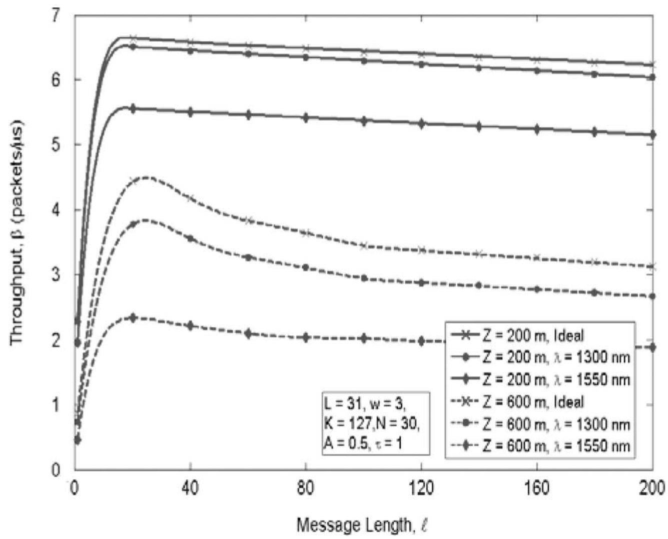

Fig. 7. Impact of dispersion: throughput vs. message length.

For convenience and sake of comparison, we have plotted the relationship between noise power and the received power for different noise sources, namely shot noise, thermal noise, and intensity noise. In our simulation, a laser diode with 0.1 nm linewidth was used at the transmitter and an avalanche photodiode with $G = 100$ was used at the receiver side. This gain contributed to 40 dB increase in shot noise. From the total noise curve, it is obvious that the system is thermal noise limited at low power, starting from -50 dBm, the shot noise dominates the performance, for power greater than -8 dBm, the effect of intensity noise will appear.

The effect of light dispersion is shown in Fig. 7, where the throughput has been plotted versus the message length for different wavelengths and distances. To visualize the results and to show the impact of dispersion (especially chromatic dispersion), a broadband source has been considered. The following parameters were used: NA $= 0.257$, $n_1 = 1.478$, $S_o = 0.097$ ps/nm$^2\cdot$km, $\lambda_o = 1343$ nm, and $\Delta\lambda = 50$ nm. The curves have the same trend as in [6]. At 1300 nm, the effect of dispersion is relatively small. For the same wavelength, the throughput degradation is more significant for larger distances that verifies (21) and (24). It is important to mention that with the R^3T protocol adopting a go-back n technique, we avoided the use of very short pulses. Therefore, the effect of dispersion over the R^3T protocol is minor when operating around 1300 nm. A dispersion compensation fiber (DCF) must be added for the case of 1550 nm. If we consider a laser with 0.1 nm spectral linewidth and a standard single-mode fiber-based LAN, the dispersion will be in the order of 1 ps at 1550 nm, which can be neglected when compared to the chip of duration $\sim$250 ps used with the R^3T protocol.

V. Conclusion

In this paper, we have studied the performance degradation of the R^3T protocol. The effect of the receiver noise has been envisaged. The Poisson and Gaussian approximations have been employed for the case of shot noise and thermal noise, respectively. The throughput, the average packet delay, and the efficiency of the R^3T protocol have been derived, simulated, and compared with the previous work in [6]. The impact of dispersion has also been considered. The following remarks can be extracted from our results.

We can tolerate the effect of noise by reasonably increasing the received power to -63 dBm and -51 dBm for the case of shot noise and thermal noise, respectively.

For small population networks, the effect of noise is dominant, while for larger networks, the MAI is the main limiting factor.

The R^3T protocol easily tolerates the effect of dispersion.

The effect of both MAI and noise exhibits an acceptable average packet delay to the R^3T protocol performance.

An asymptotic efficiency of $\sim$95% can be reached with suitable selection of code weight and code length.

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