# Internally Channel-Coded Framed Time-Hopping Fiber-Optic CDMA Communications

Paeiz Azmi, Masoumeh Nasiri-Kenari, and Jawad A. Salehi, *Member, IEEE*

***Abstract*—Due to the low cardinality of optical orthogonal codes (OOCs) with a correlation value of 1, the capability of an internal channel-coding scheme cannot be applied effectively for an increasing number of simultaneous users in a typical fiber-optic code division multiple-access (FO-CDMA) system. In this paper, we consider applying the internal channel-coding scheme to the framed time-hopping (FTH) FO-CDMA system. Due to the extremely high cardinality of the spreading sequence in FTH FO-CDMA, the technique highlights the ability of the internal channel-coding scheme to increase the effective number of users in an FO-CDMA system. For the FTH FO-CDMA system, we only consider a Poisson noise-limited channel and do not take into account the physical fiber-optic channel impairments. Our simulation and analytical results show that, due to the large cardinality of spreading codes, the capability of the internal channel-coding technique to increase the maximum number of simultaneous users becomes more obvious in the FTH FO-CDMA system.**

***Index Terms*—Fiber-optic code-division multiple access (FO-CDMA), frame time-hopping (FTH), internal channel-coding scheme, optical code-division multiple access (CDMA), optical orthogonal codes (OOCs).**

## I. Introduction

FIBER-OPTIC code-division multiple-access (FO-CDMA) systems have attracted much attention as a result of their capability to utilize the potential capacity of optical fiber, while offering asynchronous and secure communications [1]–[19]. Similar to other multiple-access techniques, most efforts in the area of FO-CDMA systems have focused on increasing and supporting the number of simultaneous users. Many techniques have been proposed to increase the number of users in the FO-CDMA network, among them using channel-coding techniques which have been given much attention in the past few years [10]–[16].

There are two schemes for applying channel-coding algorithms in FO-CDMA systems. In the first scheme, the channel-coding algorithm is externally applied to the FO-CDMA link [10]–[14]. In this case, a channel encoder is used at each transmitter to convert the data symbols into channel symbols, which are modulated and then spread by an optical spreading sequence. In employing this coding scheme, the coded FO-CDMA system needs more bandwidth than the uncoded system.

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In the second channel-coding scheme, a bandwidth-efficient scheme, namely internally applied channel codes, is used in FO-CDMA systems [1]. It has been shown that the internally coded FO-CDMA system needs the same bandwidth as the uncoded system and, therefore, the internally coded FO-CDMA system significantly outperforms the uncoded system with the same bandwidth constraint [1], [15], [16].

Practical considerations impose that a typical optical network accommodates more users with a predefined maximum acceptable bit-error probability. In an uncoded FO-CDMA system, the presence of a multiuser interference usually restricts the number of users. However, our previous results, evaluated for internally coded FO-CDMA systems with optical orthogonal codes (OOCs), show that with moderate values of average photons/nats, and even in the presence of the maximum number of users (which is usually equal to the cardinality of the OOC), the probability of error of the internally coded FO-CDMA system is much lower than the predefined maximum acceptable bit-error probability for a given practical system [1], [15], [16]. However, by using OOC with a correlation value of $\lambda = 1$, the number of users of the internally coded FO-CDMA system is bounded by the cardinality of OOC and, therefore, the ability of the internal channel-coding scheme to bring about a significant increase in the number of users is effectively reduced.

Recently, in order to overcome the above limitations, a technique named framed time hopping (FTH) was proposed. This technique provides higher cardinality than the OOC with $\lambda = 1$ [2]. This fact has encouraged us to examine the capability of our internal channel-coding scheme in increasing the number of users for a typical FTH FO-CDMA network. In our evaluation for the FTH FO-CDMA system, we only consider a Poisson noise-limited channel and do not take into account the physical fiber channel impairments. In this paper, it will be shown that with moderate values of average photons/nats and a practical maximum acceptable value for the bit-error probability, the maximum number of simultaneous users is significantly higher than the system with OOC spreading codes with $\lambda = 1$.

It should be noted that in the uncoded FO-CDMA system, the presence of multiuser interference restricts the number of users of the system and, therefore, the bandwidth efficiency of the FO-CDMA system is considered lower than that of a wavelength division multiplex (WDM) system [9]. On one hand, although using an external channel-coding scheme relatively mitigates the effect of multiuser interference, it requires more bandwidth than its corresponding uncoded system, and thus, the bandwidth efficiency of the FO-CDMA system may not be greatly improved. On the other hand, an internally coded FO-CDMA system needs the same bandwidth as the uncoded

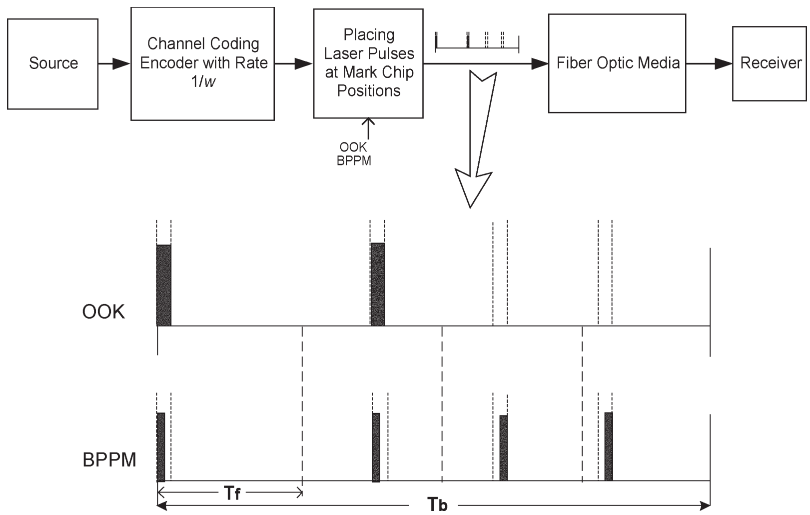


Fig. 1. Block diagram of the internally coded FTH FO-CDMA system. In this figure, the arrangements of the optical pulses for coded symbols {1,1,0,0} at an internally coded FTH FO-CDMA system are also shown for OOK and BPPM schemes.

system. By using the FTH technique in conjunction with internal coding, the number of users drastically increases, thereby enhancing the bandwidth efficiency of an optical CDMA system with respect to that of a WDM system.

In this paper, following the above introduction, Section II presents the structure of an internally coded FTH FO-CDMA system. Section III presents the analytical and computer-simulation results. Finally, Section IV concludes the paper.

## II. System Structure

### A. FTH FO-CDMA System

The FTH FO-CDMA method has been previously introduced in [2]. In this technique, the bit duration $T_{\rm b}$ is divided into $F$ chip times and pulse transmission occurs only in $w$ chips (called marked chips) out of all the $F$ chip-time positions. $w$ is the weight of the code, and its value is usually much lower than its corresponding code length $F$. In the FTH format, the $w$ pulses are located apart in sequential frames, each with duration $T_{\rm f} = T_{\rm b}/w$. In the FTH FO-CDMA system, a user-dedicated pseudorandom sequence is used in order to locate the chip-time pulse in each frame. In [2], it has been shown that the number of codewords for the FTH FO-CDMA system has a lower bound as follows:

$$N_{\rm FTH} \geq \frac{F^{w-1}}{w^w}. \quad (1)$$

For practical values of $F$ and $w$, the above number is much larger than the number of OOC codewords with auto and cross-correlation values bounded by 1, that is [17]

$$N_{\rm OOC} \leq \frac{F-1}{w(w-1)}. \quad (2)$$

Therefore, the cardinality of the FTH FO-CDMA system is much higher than the number of OOCs with the same weight and length.

### B. Internally Channel-Coded FTH FO-CDMA System

In an internal channel-coding scheme, the input data are channel coded with an easily implementable code with a rate equal to $1/w$, where $w$ is the weight of the spreading code. After encoding, the coded symbols are placed at the mark-chip positions in the signature sequences. In [1], [15], and [16], we have only considered the internal-coding scheme for an FO-CDMA system with OOC spreading codes. But, as it can be understood from the encoding procedure (see Fig. 1), the technique can be easily extended to FO-CDMA systems with any spreading sequence.

At the receiver end, three types of decoders have been proposed. In the hard-input decoder, a chip detector is used to detect the coded symbols placed at the mark-chip positions in the signature sequence. Then, after detecting the coded symbols, the data symbols are decoded by a hard-input channel decoder [1]. In a soft-input decoder, the log-likelihoods of coded symbols are calculated using the corresponding number of photoelectrons. Then, a soft-decoding algorithm uses the calculated log-likelihoods for deciding on the transmitted sequence [15]. In a multistage decoder, at the first stage, the soft-input decoder makes the primary decisions using the corresponding number of photoelectrons. Then, assuming the decisions made by the soft-input decoder are correct, this information is used by the second stage for the maximum-likelihood decoding of the transmitted sequence of the desired user, conditioned on the interfering-signal coded symbols. For other stages, the structure of the decoder is similar to the second stage, but the interfering signals are estimated using the decisions made in the previous stage [16].

It should be noted that all the proposed decoding algorithms are completely independent from the type of spreading sequences used in the system. Therefore, the internal channel-coding scheme can be directly applied to an FTH FO-CDMA system. Next, we consider a discrete model for the channel through which an internally coded FTH FO-CDMA signal is transmitted.

### *C. Channel Model of the Internally Coded FTH FO-CDMA System*

In analyzing the performance of a coded FO-CDMA communication system, the transition probabilities of the occurrence of $k_i$ photoelectrons in the $i$th mark chip, conditioned on "0" and "1" coded symbols, must be obtained (these probabilities are $P(k_i|j)\ j \in \{0,1\}$). For determining the transition probabilities, we need to have the probability distribution function of interfering pulses from the interfering users. Considering the structure of FTH spreading codes, it is obvious that the number of interfering mark chips of the interfering users in the positions of different mark chips of the desired user are independent identically distributed random variables. Furthermore, the probability distribution function of the number of interfering mark chips in each mark-chip position is a binomial random variable. In other words, if $l_i$ denotes the number of interfering mark chips in the $i$th mark chip of the desired user, we have

$$P(\mathbf{1} = [l_1, l_2, \ldots, l_w]) = \prod_{i=1}^{w} P(l_i) = \prod_{i=1}^{w} \binom{N-1}{l_i} \left(\frac{w}{F}\right)^{l_i} \left(1 - \frac{w}{F}\right)^{N-1-l_i} \tag{3}$$

where

$$P(l_i) = \binom{N-1}{l_i} \left(\frac{w}{F}\right)^{l_i} \left(1 - \frac{w}{F}\right)^{N-1-l_i} \tag{4}$$

and $N$ denotes the number of simultaneous users.

Using an ON–OFF keying (OOK) technique for modulating mark chips, a pulse is transmitted in each mark chip to represent the coded symbol "1" and "0" is indicated by zero pulse transmission [1]. In this case, assuming "0" and "1" coded symbols have equal probability, it can be easily shown that the probability of $l_i$ interfering pulses in the $i$th mark chip of the desired user can be found to be as follows

$$P(l_i) = \binom{N-1}{l_i} \left(\frac{w}{2F}\right)^{l_i} \left(1 - \frac{w}{2F}\right)^{N-1-l_i}. \tag{5}$$

In this case, the techniques used in [15] and [16] can also be applied to the coded FTH FO-CDMA communication channel, in order to calculate the transition probabilities from the following equation:

$$P(k_i|j) = \underset{l_i}{E}\{P(k_i|j,l_i)\} = \sum_{l_i} P(k_i|j,l_i)P(l_i) \qquad j \in \{0,1\}. \tag{6}$$

Using the binary pulse-position modulation (BPPM) technique for modulating mark chips, each mark-chip interval is divided into two time slots. For this case, the coded symbol "1" is represented by a pulse in the first time slot, and "0" is represented by a pulse in the second part of the chip interval [1] (see Fig. 1). In this case, assuming that "0" and "1" coded symbols have equal probability, it can be easily shown that the probability of $l_{1i}$ interfering pulses in the first time slot and $l_{2i}$ pulses in the second time slot, conditioned on the occurrence of $l_i$ interfering mark chips in place of the $i$th mark chip of the desired user, can be found as follows:

$$P(l_{1i}, l_{2i}) = \binom{l_i}{l_{1i}, l_{2i}} \frac{1}{2^{l_i}}. \tag{7}$$

Therefore, we have

$$\begin{aligned} P(l_{1i}, l_{2i}, l_i) &= P(l_{1i}, l_{2i}|l_i)P(l_i) \\ &= \binom{l_i}{l_{1i}, l_{2i}} \binom{N-1}{l_i} \frac{1}{2^{l_i}} \left(\frac{w}{F}\right)^{l_i} \left(1 - \frac{w}{F}\right)^{N-1-l_i} \\ &\quad \text{where } l_{1i} + l_{2i} = l_i. \end{aligned} \tag{8}$$

For this case, the techniques used in [15] and [16] can also be applied to the coded FTH FO-CDMA communication channel, in order to calculate the transition probabilities from the following equation:

$$\begin{aligned} P(k_i|j) &= \underset{l_{1i}, l_{2i}, l_i}{E} \{P(k_i|j, l_{1i}, l_{2i}, l_i)\} \\ &= \sum_{\substack{l_{1i}, l_{2i}, l_i \\ l_{1i}+l_{2i}=l_i}} P(k_i|j, l_{1i}, l_{2i}, l_i) P(l_{1i}, l_{2i}, l_i) \\ &\quad j \in \{0,1\}. \end{aligned} \tag{9}$$

Comparing (3)–(9) with the corresponding equations obtained for FO-CDMA with OOC spreading codes in [15] and [16], it can be observed that the transition probabilities of the internally coded FTH FO-CDMA system is the same as the FO-CDMA system with OOCs. Therefore, the results that we have found in [15] and [16] for OOCs can be directly used for the FTH case, with the exception that in the OOC case, the number of users $N$ must comply with (1), and in the FTH case, $N$ must comply with (2). In other words, for evaluating the performance of an internally coded FTH FO-CDMA system from the results of [15] and [16], we should only consider larger values for $N$. Hence, in this paper, we will not rederive the equations of transition probabilities, and we will only present and discuss the numerical and simulation results in the next section.

## III. Numerical and Simulation Results

In Figs. 2 and 3, we present computer-simulation results on the bit error rate (BER) of an internally coded FO-CDMA system with FTH and OOC spreading codes. In Fig. 2, the plots are obtained for OOK chip modulation, and in Fig. 3, for the other chip-modulation technique, namely, BPPM. The channel-coding algorithm that is used in all the simulations is super orthogonal codes (SOC) [1], [15], [16] with rate 1/2. The FTH and OOC spreading codes are with $F = 7$, $w = 2$, and $N = 2$. Furthermore, nonlinear channel impairments and background and dark-current noises are neglected.

Comparing the results of the BER of FO-CDMA systems with FTH and OOC spreading codes, it can be observed that the BER of the systems are nearly equal. In other words, in spite

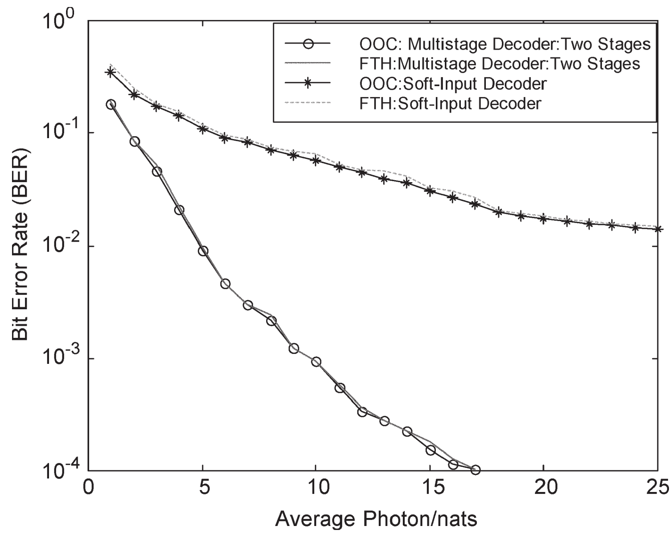


Fig. 2. Simulation curves of BER versus average photons/nats for the internally coded FO-CDMA system with OOC and FTH spreading sequences, with $F = 7$, $w = 2$, and $N = 2$. The chips are modulated with the OOK technique.

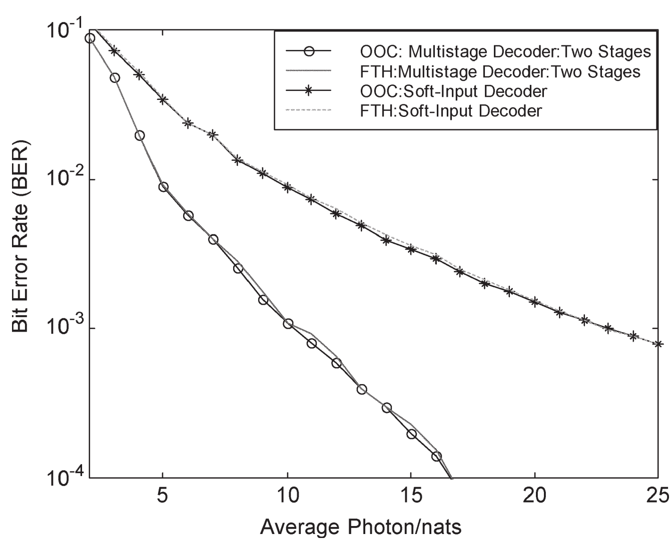


Fig. 3. Simulation curves of BER versus average photons/nats for the internally coded FO-CDMA system with OOC and FTH spreading sequences, with $F = 7$, $w = 2$, and $N = 2$. The chips are modulated with the BPPM technique.

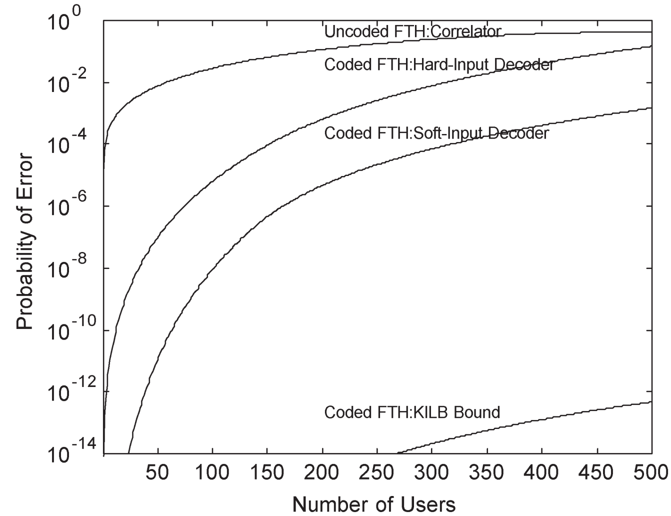


Fig. 4. Simulation curves of probability of error versus number of users for FO-CDMA systems with FTH spreading sequence $F = 2000$ and $w = 8$. The chips are modulated with the OOK technique at 25 photons/nat.

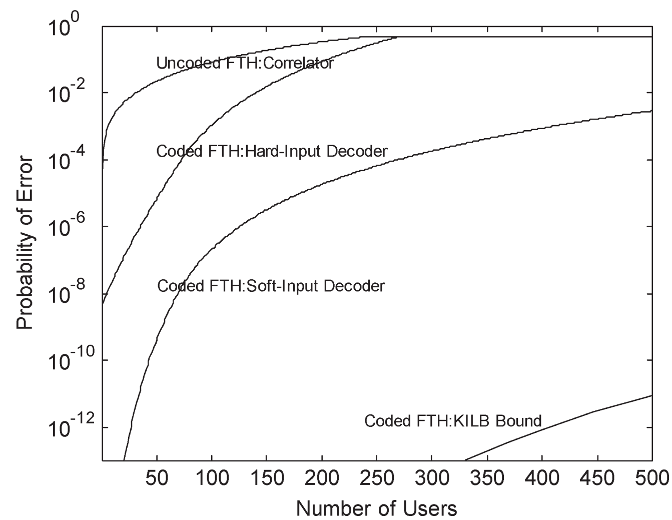


Fig. 5. Simulation curves of probability of error versus number of users for FO-CDMA systems with FTH spreading sequence with $F = 2000$ and $w = 8$. The chips are modulated with the BPPM technique at 25 photons/nat.

of the nonoptimality of FTH codes, its performance is nearly the same as the optimum OOCs with auto and cross-correlation values bounded by 1 [2], [17].

In Figs. 4 and 5, upper bounds on the probability of error for FTH FO-CDMA systems for the cases of uncoded and internally channel coded with hard-input and soft-input decoders are computed. Furthermore, the results are compared with a bound on the probability of error by employing a multistage decoder that is known as known interference lower bound (KILB) [16], [19]. It should be noted that based on the results of the previous section, the equations that have been presented in [1, eqs. (7)–(22)], [15, eqs. (19)–(26)], and [16, eqs. (16)–(32)] are used for obtaining the upper bounds for this paper. The channel-coding algorithm used in all evaluations is SOC [1], [15], [16] with rate 1/8, and the FTH and OOC spreading codes are with $F = 2000$ and $w = 8$. Furthermore, because of the use of a fiber-optic channel, background noise and dark-current noise are neglected. All the plots in Figs. 4 and 5 are depicted for the case that the average number of photons/nats is fixed to 25. Note that results presented in Figs. 4 and 5 for the cases of $N \leq 35$ are the same as the results on the internally channel-coded FO-CDMA system with OOC. This is due to the cardinality of OOC, i.e., $N = 35$ for $F = 2000$, and $w = 8$, which is much less than the cardinality of the FTH spreading sequence.

To show the capability of the internal channel-coding scheme to increase the number of users in the FTH FO-CDMA system, we assume that the maximum acceptable bit-error probability of an internally coded FO-CDMA is $10^{-10}$. From Figs. 4 and 5, it can be seen that with an average number of photons/nats of 25, whether the OOK or BPPM technique is used for modulating the chips, the uncoded FO-CDMA system cannot provide the desired bit-error probability. But if the internal channel-coding technique is applied to the FTH- or OOC-based FO-CDMA system, by using a hard-input decoder, the network may support up to five users.

By using a soft-input decoder, the number of users of the internally coded FTH FO-CDMA system may reach up to 60, if the OOK technique is used, and up to 40, if the BPPM technique is used. Considering the KILB curve, by using a multistage decoder, the number of users may even be higher. However, by using OOC for spreading the signals of the internally coded FO-CDMA system, the maximum number of users will be 35, which is the cardinality of OOC. Therefore, it can be seen that by using FTH along with the internal channel-coding technique, one can increase the number of users in a typical FO-CDMA system.

## IV. Conclusion

In [1], it was shown that due to the low cardinality of the OOC spreading sequence, for moderate average number of photons/nats, and for practical values of the probability of errors, the capability of the internal channel-coding scheme cannot be applied effectively in increasing number of simultaneous users in a typical fiber-optic code division multiple-access (FO-CDMA) network. In other words, by using the internal channel-coding scheme to mitigate noise and multiuser interference, the number of users is limited by the cardinality of the optical orthogonal codes (OOC) sequences and not necessarily by the noise or multiuser inference. In this paper, in order to overcome this weakness, we consider applying the internal channel-coding scheme to a newly proposed technique for the FO-CDMA system, namely, the framed time-hopping (FTH) system [2]. It has been shown that if the FTH technique is used, due to its extremely high cardinality of spreading sequence, the internal channel-coding method brings about more simultaneous users. Therefore, the FTH technique highlights the ability of the internal channel-coding scheme in increasing the effective number of users in an optical CDMA system.

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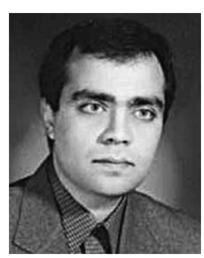

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He was a full-time Research Assistant at the Communication Science Institute at USC, from 1981 to 1984, engaged in research in the area of spread-spectrum systems. From 1984 to 1993, he was a Member of Technical Staff with the Applied Research Area at Bell Communications Research (Bellcore), Morristown, NJ. From February to May 1990, he was with the Laboratory of Information and Decision Systems at the Massachusetts Institute of Technology (MIT), Cambridge, as a Visiting Research Scientist conducting research on optical multiple-access networks. From 1997 to 2003, he was an Associate Professor, and is currently a Full Professor with the Electrical Engineering Department, Sharif University of Technology (SUT), Tehran, Iran. From fall 1999 until fall 2001, he was the Head of Mobile Communications Systems Group and Codirector of the Advanced and Wideband CDMA Lab at Iran Telecommunication Research Center (ITRC), conducting research in the area of advance CDMA techniques for optical and radio communications systems. Since 2003, he has funded and directed the Optical Network Research Laboratory at the Electrical Engineering Department of SUT, where advanced experimental and theoretical researches on futuristic optical networks are conducted. His current research interests are in the areas of optical multiaccess networks, in particular, optical orthogonal codes (OOCs), fiber-optic CDMA (FO-CDMA), femtosecond or ultrashort light-pulse CDMA, spread-time CDMA, holographic CDMA, wireless indoor infrared CDMA, all-optical synchronization, and applications of erbium-doped fiber amplifiers (EDFA) in optical systems. His work on optical CDMA resulted in 11 U.S. patents.

Dr. Salehi is a recipient of the Bellcore's Award of Excellence. He has also received the Outstanding Research Award of the Electrical Engineering Department at SUT, in 2002 and 2003, the Outstanding Research Award of SUT, in 2003, the Nationwide Outstanding Research Award from the Ministry of Higher Education, in 2003, and the Special Nationwide Outstanding Research Award in 2004. Recently, he was introduced as being among the 250 prominent and most influential researchers worldwide by Institute for Scientific Information (ISI), highly cited in the computer-science category. He is the corecipient of IEEE's Best Paper Award from the International Symposium on Communications and Information Technology, Japan, October 2004. He assisted, as a Member of the Organizing Committee, in organizing the first and the second IEEE Conference on Neural Information. Since May 2001, he has been serving as Editor for Optical CDMA of the IEEE TRANSACTIONS ON COMMUNICATIONS.