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A New Channel Allocation for Eliminating Intermodulation

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Abstract*—For multichannel communication, a frequency allocation scheme has been presented that eliminates the effect of intermodulation distortion of all odd orders and that of harmonics. Our allocation is optimal in the sense that minimum total occupied bandwidth is used. Our allocation offers the same EVM (error vector magnitude) vs. P_{in} (channel RF input power) curve, independent of the selected channel. We applied our ideas for an 8 channel RoF system.*

Index Terms*—Frequency allocation, intermodulation, harmonics, frequency invariance*

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I. INTRODUCTION

In a multichannel communications system, several nonlinearities occur. Nonlinearity produces harmonics and intermodulation. The effect of the third-order intermodulation is the most problematic one because its frequency is near to the useful signal. Special arrangement of subcarrier frequencies can eliminate this effect. In this paper, we solve the problem in general how to eliminate the effects of intermodulation distortion of odd orders and that of harmonics so that the total occupied bandwidth is minimum. Our ideas are valid in general, independently of the applied communication technology and the types of nonlinearities. However, we apply our theoretical results in the design of an 8 channel Radio over Fiber (RoF) system.

To introduce the topic in general, we must obtain overviews about multichannel technologies [9,10], channel allocation [11] and optical nonlinearities [12].

Considering multichannel technologies, the following abbreviations occur: RoF (Radio over Fiber), WDM (Wavelength Division Multiplexing), DWDM (Dense WDM), CWDM (Coarse WDM), OADM (Optical Add-Drop Multiplexer).

RoF is overviewed first [9]. Despite the remarkable growth in communication technologies, there is an increased requirement for integration of heterogeneous technologies, particularly mobile and wireless communications, into a backbone network that can provide mobile, broadband, reliable and ever-present services to end users. Radio-over-Fiber technology appears to be an emerging and efficient solution towards the seamless integration of optical and wireless networks for future broadband communications. This paper discusses the concept and the fundamental issues of radio over fiber technology and provides a brief survey on the current state of the art. Additionally, it presents an overview of the ongoing work at the Research and Development for Telecommunications Laboratory (RDTL) of the Technological Educational Institution (TEI) of Athens.

The next topic is WDM [10]. As speed & bandwidth has always been a cause of concern in communication network, WDM emerges as a vital solution to these problems. The problem arises when the demand for bandwidth in a fiber optic network exceeds the current capacity, WDM helps in expanding the capacity of a fiber optic network without requiring additional fiber. The decision problem is to find the most cost-effective combination of WDM equipment and fiber that increases the capacity of the network to a point where all the expected demand can be handled. This paper presents an overview about WDM technology and recent developments in this field and how the overall capacity of the communication network can be incremented using this technology.

Channel allocation is the third topic [11]. The study of the channel allocation problem has been successfully developed during the last decade. Several techniques such as genetic algorithm, artificial neural network, simulated annealing, tabu search and others have been used. This book is devoted to compiling all the techniques that have been used to solve the channel allocation problem. Each of the methods is described fully in a manner that explains the essential parts of how the techniques are formulated and applied in solving the problem. This textbook will be helpful to students studying communications or researchers as it compiles all the techniques used since this problem was first solved until the present.

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Finally, an overview of the optical nonlinearities is necessary [12]. Optical nonlinearities give rise to many ubiquitous effects in optical fibers. These effects are interesting in themselves and can be detrimental in optical communications, but they also have many useful applications, especially for the implementation of all-optical functionalities in optical networks. In the present paper, the author briefly reviews the different kinds of optical nonlinearities encountered in fibers, pointing out the essential material and fiber parameters that determine them. The author describes the effects produced by each kind of nonlinearity, emphasizing their variations for different values of essential parameters. Throughout the paper, the author refers to recent systems applications in which these effects have been dealt with or exploited.
Three different allocations have been compared in Table I and Fig. 1.

TABLE I. COMPARED ALLOCATIONS

	CHANNEL 1 MHZ		CHANNEL 2 MHZ		CHANNEL 3 MHZ		CHANNEL 4 MHZ	
UNIFORM	280	320	330	370	380	420	430	470
OUR SCHEME	1245	1285	1325	1365	1485	1525	1565	1605
ITU	280	320	330	370	480	520	730	770

In all three cases, the bandwidth is 40 MHz. The gaps between the channels are different. The gap for uniform allocation is 10 MHz, and constant. In our scheme, the gap is varied [2], and details are found later. ITU allocation has a varied gap as well [1], which increases with frequency.

The total occupied bandwidth is the smallest for the uniform allocation, the next one is our scheme with optimum total bandwidth, and the largest bandwidth is necessary for the ITU allocation.

We prove that our allocation eliminates the effect of all harmonics and intermodulation of odd order that can be eliminated by proper allocation, and simultaneously, the total occupied bandwidth is minimum.

EVM (error vector magnitude) is a basic characteristic of digital communication channels [4]. Its definition is square root of the squared average distance between an ideal and real decision. As it is influenced by noise, it strongly depends on the signal-to-noise ratio. For a specific channel, when the noise is given, it is enough to obtain its dependence on the channel input power. Certainly, it is frequency-dependent in general, which will be studied in more detail.

II. RESULTS

The simplest case is investigation of elimination of the effect of third-order intermodulation for two spectral lines (Fig. 2).

In Fig. 2, channels plotted in green are too near to each other; thus, the third-order intermodulation product falls into the channel on the right. To avoid this, the gap size has to be equal to B.

In Fig. 2. the third-order intermodulation farthest from the channel on the left has been investigated. Now, the nearest will be investigated. In Fig. 3, it is shown that if the two original spectrum lines have B/2 or smaller frequency difference, and the lower frequency is at the edge of the channel, then the third-order intermodulation product is within the same channel. This implies that the effect of the third-order intermodulation cannot be eliminated by allocation. In this case, a predistorter can be applied.

The next step is repetition of the procedure outlined in Fig. 2. The next gap is equal to the whole bandwidth of previous channels with the gap in between.

The allocation shown in Fig. 4 eliminates the effect of all third-order allocations that can be eliminated by allocation, and the total occupied bandwidth is minimum. Harmonics are eliminated in such a way that the lowest frequency of the channels is chosen equal to the total occupied bandwidth. Based on Fig. 4, the maximum number of channels is determined when the channel bandwidth is given (40 MHz), as a function of the maximum modulation frequency of the laser diode (Fig. 5).
Thus, we generalize our procedure.
First step: Three spectral lines. Let the spectral line frequencies be f1, f2, f3, and we assume

$$B \ll f_k \tag{1}$$

where k=1,2,3 and that all spectrum lines fall into the lowest channel. Eq. (1) is necessary for the transition from (2) to (3). Third-order intermodulation frequencies are:

$$I_3 = \pm f_1 \pm f_2 \pm f_3 \tag{2}$$

where any two may coincide. The problem is the greatest value of I_3 above the lowest channel.
In Eq. (2), two or three negative signs are not allowed, because then the intermodulation will be below the channel. Similarly, three positive signs are not allowed as well, because all frequencies are placed between a certain frequency and twice as much [2]:

$$I_3 = -f_1 + f_2 + f_3 \quad (3)$$

It can be easily seen that I_3 will be the highest if f_1 is lower, and the other two frequencies are at the higher edge of the channel. In that case

$$I_3 = 2f_2 - f_1 \quad (4)$$

and from this point on, the continuation is the same as that for two spectrum lines.
Now, the validity will be checked for five spectrum lines. Let the frequencies be f_1, f_2, f_3, f_4, and f_5, where

$$B \ll f_k \quad (5)$$

k=1,2,3,4,5 with the condition that all five are within the lowest channel. Frequencies of the fifth-order intermodulation are:

$$I_5 = \pm f_1 \pm f_2 \pm f_3 \pm f_4 \pm f_5 \quad (6)$$

The problem is the maximum value of I_5 above the lowest channel.
In Eq. (6), five, four, or three negative signs are not allowed because in that case I5 would be below the channel. Similarly, five or four positive signs are not allowed as well, because we seek intermodulation product above a certain frequency and its double. Thus:

$$I_5 = -f_1 - f_2 + f_3 + f_4 + f_5 \quad (7)$$

It is easy to understand that I_5 is maximum if f_1 and f_2 are lower, and f_3, f_4, and f_5 are at the higher edge of the channel. In that case

$$I_5 = 3f_3 - 2f_2 \quad (8)$$

As f_3=f_2+B, I_5=f_2+3B, or in other words, the gap between the lowest and second lowest channels is 2B. As the lowest two channels together with the gap have a bandwidth of 4B, the next gap is also 4B. Repeating this trick, the gap between the first and second channel 4-tuple is 12B and so on.
Similarly, in the case of 2n+1 spectral lines, where n is an arbitrary positive integer,

$$I_{2n+1} = (n+1)f_{n+1} - nf_n \quad (9)$$

Therefore, the gap between the first two channels is n*B. With this construction, the effect of all intermodulation products of order 2n+1 has been eliminated, and simultaneously, the total occupied bandwidth is minimum.
At the kth step, in case of 2n+1 spectral lines, the gap width is

$$G = (k > 1)3^{k-1} + (k = 1)n + (k > 1)(n > 1)(n - 1)3^{k-2} \quad (10)$$

where the gap bandwidth is G*B. Values of relational operations are 1 or 0 when the result is true or false, respectively.
Some values of G are summarized in Table II.

TABLE II. VALUES OF G IN EQ. (10) ACCORDING TO SOME SMALL VALUES OF K AND N

N	1	2	3	4	5
NUMBER OF SPECTRAL LINES	3	5	7	9	11
K (STEP NUMBER)	VALUES OF G				
1	1	2	3	4	5
2	3	4	5	6	7
3	9	12	15	18	21
4	27	36	45	54	63

Remark: Every intermodulation of even order is outside the total occupied band. Therefore, this allocation eliminates all intermodulation products that can be eliminated by allocation.
A four-channel, four-subcarrier RoF system has been investigated using the analysis program AWR. Details of the system diagram are found in Fig. 2. Channel frequencies are given in Table I. The channels have been excited by 64QAM 802.11a signal of variable power. In one run, four channels have been investigated. Then,

the EVM vs. P_{in} curves are plotted (Fig. 6a, b, and c).
Maximum deviation between channels is far from the smallest for our allocation scheme. This implies that EVM vs. P_{in} curve is invariant for the channel selection, or in other words, is frequency invariant.
The reason of this observation is that all third-order products have been in gaps between channels, and higher-order terms are negligible in our example.
Some more explanation is needed for why our allocation is better in this respect than ITU allocation. The reason is that the first two gaps are smaller for ITU allocation than necessary; therefore, not all third-order intermodulation have been eliminated.
Another possible question is why the deviation is not zero in Fig. 6b. The origin of the nonzero deviation is threefold: 1. Noise, 2. Third-order intermodulation within the same channel where the useful signals are located, 3. Higher-order intermodulation. Intermodulation within the same channel can be decreased by using a predistorter [8]. Higher-order intermodulation can be decreased by applying wider gaps, Table II. The presence of higher-order intermodulation explains the increase of the error curve at higher levels. At small levels, noise starts to dominate.
Results of this section are valid for arbitrary spectral line number of odd order, because time-domain analysis takes it into account automatically.
The investigated system is shown in Fig. 7. The idea behind is that the laser diode, the optical cable, and the photo diode have been modeled by the nonlinear amplifier A5; thus, everything has been modeled in the microwave region. Here, the analyzer has been synchronized to channel 3. To synchronize it to a different channel, the following things have to be done:
Left input port of the analyzer is connected to the input of the new channel.
The block “Change FC” right of the new channel is deleted.
Bandpass channel filter of the receiver is replaced by the bandpass transmitter channel filter of the selected channel.
Input of the amplifier A4 is connected to the low-pass filter after LO in the new channel.
To investigate different allocations,
The frequencies of the four LO are set accordingly.
The four low-pass filters after LOs are set accordingly.
The four transmitter bandpass filters are set accordingly.
The same holds true for the receiver bandpass filters.

Picture of the realized system is shown in Fig. 8.
In Fig. 8, left side is the transmitter, right side is the receiver. The laser and photo diodes should be connected to the SMA connectors at the front middle. Copper shielding is for filter circuits. White boxes are SAW filters. Black boxes at the left are for supply interconnection and stabilized power supply. SMA connectors at the far end are for LO inputs. SMA connectors near SAW filters are measurement points.

III. DISCUSSION

New channel allocation has been introduced. It is proved that the same construction rules are valid for all spectral line numbers of odd order.
Advantages are manifold. This allocation is optimum in the sense that eliminates the effects of all harmonics and intermodulation while occupying minimum total bandwidth. Much less total occupied bandwidth is required than that for ITU suggestion.
Next, the EVM vs. P_{in} curve has been investigated for different allocations, and frequency invariance has been observed for our allocation scheme.
Our results have many advantages. For the same input power, the same quality can be guaranteed independent of the channel selection. Also, quality is not sensitive for small frequency deviations.
LIST OF ABBREVIATIONS
RoF (Radio over Fiber)
WDM (Wavelength Division Multiplexing)
DWDM (Dense WDM)
CWDM (Coarse WDM)
OADM (Optical Add-Drop Multiplexer)

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Figure captions

Fig. 1. Comparison of channel allocations: horizontal axis – frequency; vertical axis: absolute value of filter transfer functions

Fig. 2. Determination of the necessary gap between channels. The same bandwidth B is assumed for all channels

Fig. 3. Generation of third-order intermodulation product within the channel of useful signals

Fig. 4. Repetition of the procedure in Fig. 2, k is the step number

Fig. 5. Channel number as a function of the maximum modulation frequency. Horizontal axis: modulation frequency in MHz, vertical axis: Channel number. Bandwidth is 40 MHz. In our experimental system, modulation frequency is 2700 MHz, corresponding to eight channels

Fig. 6a. EVM vs. P_{in} for uniform allocation, in four different channels. Maximum deviation between the curves is 7.575%, at 0 dBm. Horizontal axis: P_{in} (dBm), vertical axis: EVM (%). Different channels are plotted in different colors

Fig. 6b. EVM vs. P_{in} for our allocation scheme, in four different channels. Maximum deviation between the curves is 0.8%, at 0 dBm. Horizontal axis: P_{in} (dBm), vertical axis: EVM (%). Different channels are plotted in different colors

Fig. 6c. EVM vs. P_{in} for ITU allocation, in four different channels. Maximum deviation between the curves is 6.438%, at 0 dBm. Horizontal axis: P_{in} (dBm), vertical axis: EVM (%). Different channels are plotted in different colors

Fig. 7. The four-channel optical communication system investigated in AWR

Fig. 8. The realized system

Fig. 1.

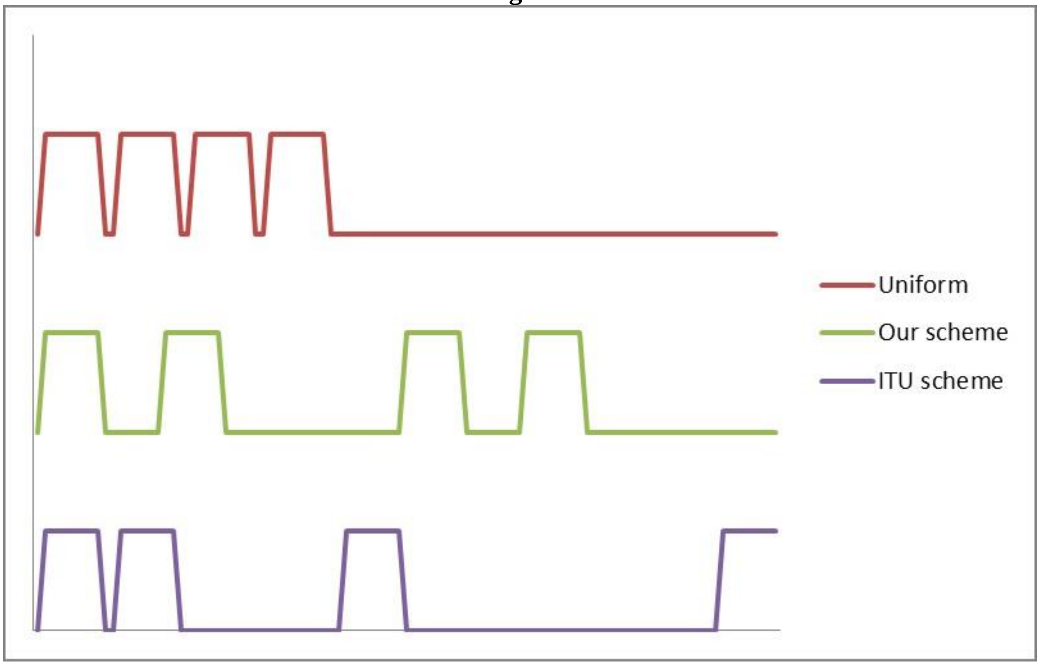


Fig. 2.

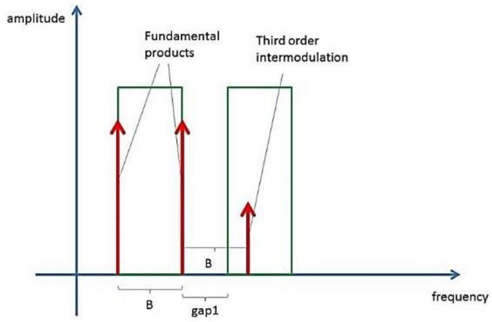


Fig. 3.

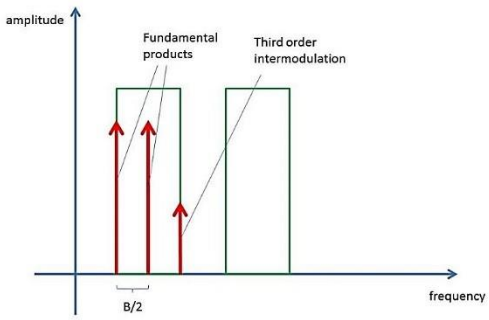


Fig. 4.

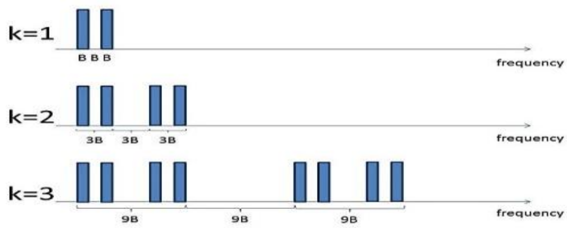


Fig. 5.

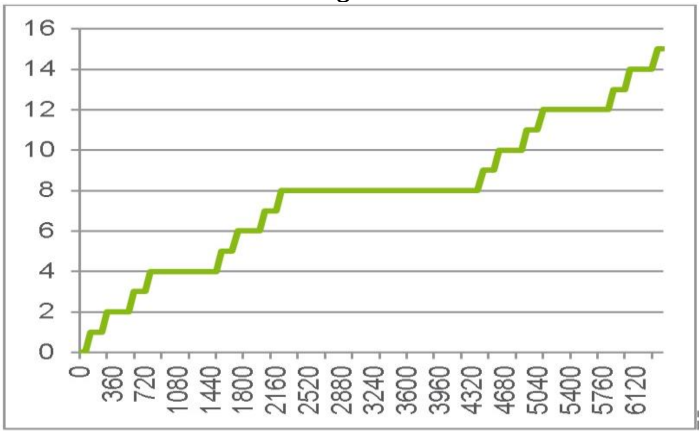


Fig. 6abc.

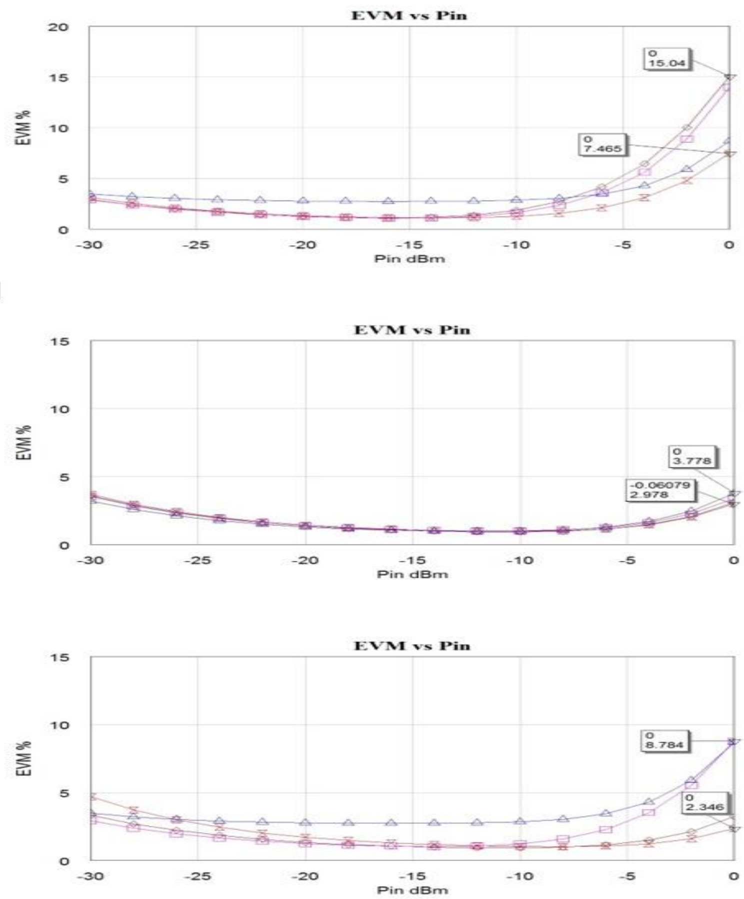


Fig. 7.

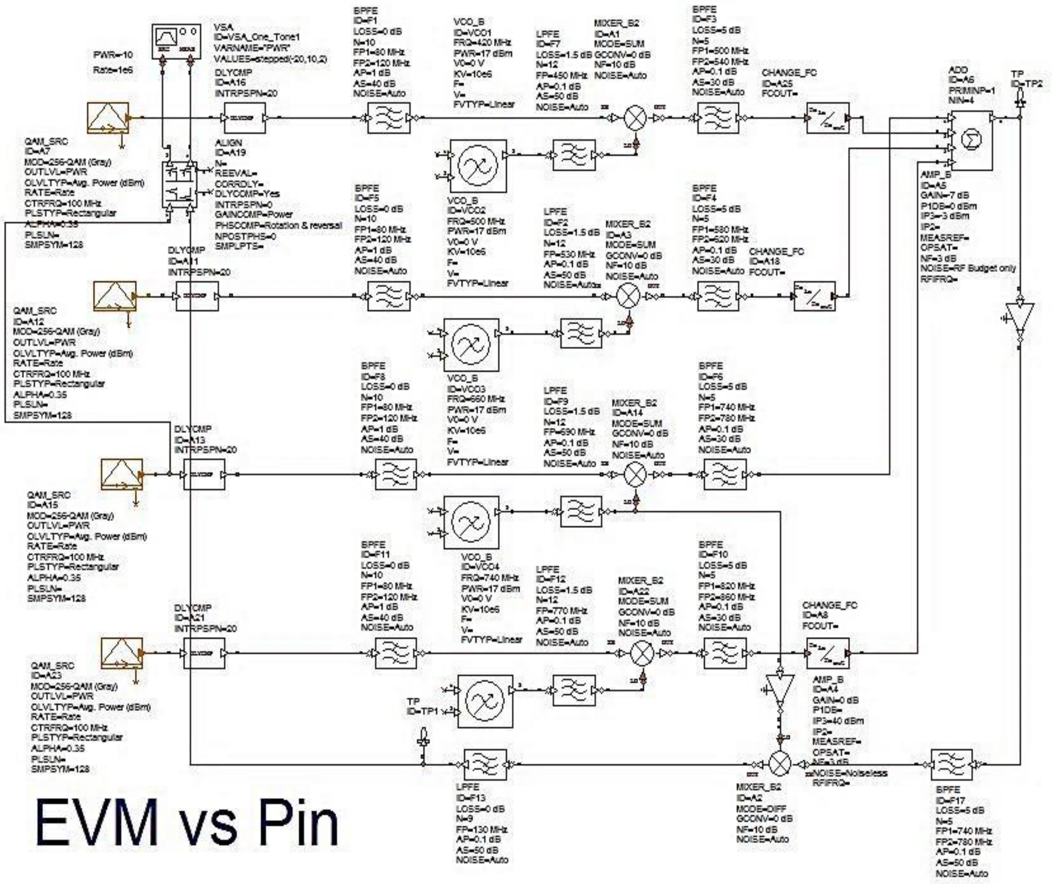
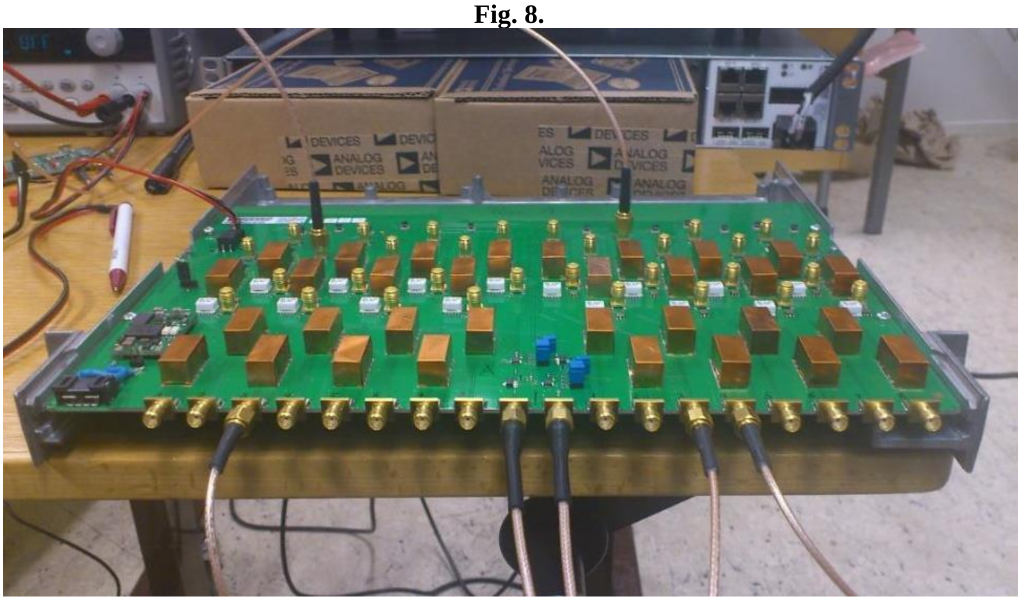


Fig. 8.



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