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# A new approach to increasing the bandwidth of fiber-optic communication systems

# *Fiber-optik haberleşme sistemlerinin bant genişliğinin artırılması için yeni bir yaklaşım*

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# A New Approach to Increasing the Bandwidth of Fiber-Optic Communication Systems

### *Highlights*

- *The new approach is introduced to increase bandwidh of communication systems.*
- *The approach contributes to the economic sustainability of communication network systems.*
- *The systematic approach proposes the use of unused harmonic components of non-linear harmonic distortion.*

### *Graphical Abstract*

*In this study, a theoretical systematic approach is introduced as a solution of the bandwidth problem of multi-tone network systems.*

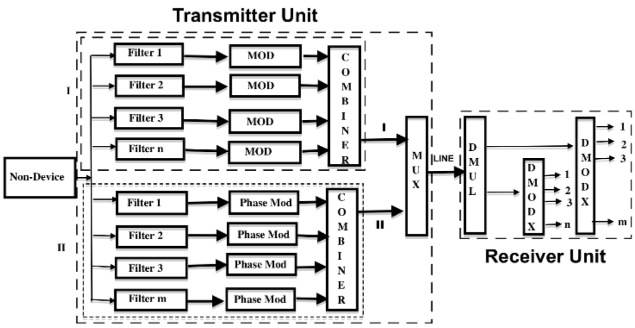


**Figure.** Block structure of the whole system

### *Aim*

*This approach aims to increase the bandwidh of communication systems.*

### *Design & Methodology*

*This systematic approach proposes the use of unused harmonic components of non-linear harmonic distortion produced by the semiconductor laser diode, which is used as a source in the infrastructure of the fiber optic communication system.*

### *Originality*

*The use of unused harmonic components of non-linear harmonic distortion is firstly introduced.*

### *Findings*

*In order to separate unused harmonic distortion frequency components from the others, it is possible to add a protocol to each harmonic distortion difference frequency signal, or by intermodulation distortion (IMD) phase modulation, or to use both protocol and IMD phase modulation together.*

### *Conclusion*

*This systematic approach increases the bandwidth of the communication networks by using unused harmonic components of non-linear harmonic distortion.*

### *Declaration of Ethical Standards*

*The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.*

# A New Approach to Increasing the Bandwidth of Fiber-Optic Communication Systems

*Araştırma Makalesi / Research Article*

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**ABSTRACT**

In this study, a theoretical systematic approach is introduced as a solution of the bandwidth problem of multi-tone network systems. This systematic approach proposes the use of unused harmonic components of non-linear harmonic distortion produced by the semiconductor laser diode, which is used as a source in the infrastructure of the fiber optic communication system. In order to separate these unused harmonic distortion frequency components from the others, it is possible to add a protocol to each harmonic distortion difference frequency signal, or by intermodulation distortion (IMD) phase modulation, or to use both protocol and IMD phase modulation together. Thus, all harmonic distortion frequency components can be separated theoretically. Thus, it is recommended to use IMD difference frequency components in multi-tone-input subcarrier fiber optic or similar communication systems in the same transmission medium. We think that if this technique is used, it will make a great contribution to increasing the bandwidth of fiber optic communication and network systems.

**Keywords: Phase IMD, bandwidth, harmonic distortion, non-linear distortion.**

# Fiber-Optik Haberleşme Sistemlerinin Bant Genişliğinin Artırılması için Yeni Bir Yaklaşım

**ÖZ**

Bu çalışmada, çok-ton girişli ağ sistemlerinin bant genişliği sorununun çözümüne teorik sistematik bir yaklaşım getirilmiştir. Bu sistematik yaklaşım, fiber optik haberleşme sisteminin alt yapısında kaynak olarak kullanılan yarıiletken lazer diyotun üretmiş olduğu doğrusal olmayan harmonik bozulmanın kullanılmayan harmonik bileşenlerinin kullanımını önermektedir. Bu kullanılmayan harmonik bozulma frekans bileşenlerini diğerlerinden ayırmak için, her bir harmonik bozulma fark frekans sinyaline bir protokol eklenebilir veya intermodülasyon bozulma (IMD) faz modülasyonu uygulanabilir veya hem protokol hem de IMD faz modülasyonu beraber kullanılabilir. Böylece tüm harmonik bozulma frekans bileşenlerini ayrıştırma işlemi teorik olarak yapılabilmektedir. Bu nedenle, çok ton-girişli alt taşıyıcılı fiber optik ya da benzeri haberleşme sistemlerindeki IMD fark frekans bileşenlerini aynı iletim ortamı içerisinde kullanılması önerilmektedir. Bu tekniğin kullanılması halinde fiber optik haberleşme ve ağ sistemlerinin bant genişliğinin artırılmasına büyük katkı sağlayacağını düşünüyoruz.

**Anahtar Kelimeler: Faz IMD, bant genişliği, harmonik bozulma, doğrusal olmayan bozulma.**

## 1. INTRODUCTION

Fiber optic networks are widely used in backhaul network systems. In these network systems, laser diode is mostly used as signal source. The laser diode and semiconductor parts used as signal sources are physically non-linear. Although the bandwidth of these network systems is limited due to the physical properties of the materials used in the infrastructure, the number of users is not limited; on the contrary, it is increasing. Especially in data transmission, this need is constantly increasing day by day. Corporate companies and technology are constantly in search of a solution to this problem.

Network structures can be divided into two parts. The first is the backhaul networks used by the companies or institutions or organizations operating the commercial communication system, while the other is the clients. While the size of the data packet and the number of sends per unit time are important in backhaul networks, it is important that the number of users per unit time is high in the client part. However, recently, the size of the data packets used by the clients has been growing day by day. The existing infrastructure and modulation techniques are insufficient to meet this data packet traffic. For this reason, new modulation techniques and new technology communication systems are being researched to meet this requirement.

Today, due to the increase in data usage and the desire to transfer larger data packets per unit time, the bandwidth of commercial networks is insufficient. In order to meet this data packet traffic, new networks are established and using different modulation techniques increases the bandwidths of the existing ones. The main ones are

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asymmetric digital subcarrier line (ADSL), ATC (Sub-carrier multiplexing, Sub-Carrier Multiplexing, SCM), digital subcarrier line (DSL), ultra-high speed digital subcarrier line (Very-high speed Digital Subcarrier Line, VDSL), discrete multitone (DMT) and discrete wavelet multitone (DWMT), cross quadrature amplitude modulation (X-QAM), quadrature phase-shift keying (QPSK), wavelength-division multiplexing (WDM), dense wavelength-division multiplexing (DWDM), time division multiple access (TDMA), frequency division multiple access (FDMA), code division multiple access (CDMA), orthogonal frequency-division multiplexing (OFDM) and orthogonal frequency division multiple access (OFDMA( derivatives are widely used. The infrastructure of the network system cannot be renewed very quickly due to economic and physical reasons.

There are studies in the literature for harmonic, asymmetric and amplitude control [1-2]. On the other hand, the next generation communication systems will be quantum communication systems, free space light wave and plasmonics communication or similar systems [3]. These systems will be more secure than today's systems, and the bandwidth will be larger [4-7]. Quantum metropolitan networks will be used in the backhaul networks of the future [8]. With the "spooky" quantum, even an unexpected era can be opened in communication systems [9-10]. These studies are currently in the research/development stage. However, we think it will definitely be used in the future.

## 2. PRODUCTION AND SEPARATION OF FREQUENCY COMPONENTS

All of the real physical systems used in communication systems are non-linear. Therefore, all physical systems produce harmonic distortion and their bandwidth is also limited. This is independent of the system's input/output features. Systems can be single input or multiple inputs. In contrast, single-tone or multi-tone signals can be applied to single-input systems. This is completely dependent on the system design developed according to the need and purpose. The general form of the multi-tone signal to be applied to the input of a system is defined as

$$U = U_0\cos(\omega_0 t+\phi_0)+U_1\cos(\omega_1 t+\phi_1)+ U_2\cos(\omega_2 t+\phi_2)+....+U_n\cos(\omega_n t+\phi_n) \quad (1)$$

Equation (1) represents the amplitudes of the passing $U, U_0, U_1, U_2, ...U_n$ input signals, $\omega, \omega_0, \omega_1, \omega_2, ...\omega_n$ represent the frequencies and $\phi_0, \phi_1, \phi_2, ...\phi_n$ represent the phases. The carrier signal can be defined as represented by $U_0\cos(\omega_0 t+\phi_0)$ and $U_0$ represents the amplitude of the carrier signal. Thus, the generalized sum transfer function (TT) of any non-linear system is

$$TT = A + H_1 u + H_2 u^2 + H_3 u^3 + ......H_n u^n \quad (2)$$

where A represents any constant of the system, $H_1, H_2, H_3, ..., H_n$ represent the amplitudes of the harmonics or the coefficients of the nuclei of the Volterra series. Harmonic amplitudes can theoretically be made up to the nth order. In Equation (3), if the harmonic coefficients of the non-linear system sensitive to nth degree phase change, the Volterra core coefficients are,

$$\begin{aligned}
H_1 &= \begin{bmatrix} U_0\cos(\omega_0 t+\phi_0)+U_1\cos(\omega_1 t+\phi_1)+U_2\cos(\omega_2 t+\phi_2)+ \\ ....+U_n\cos(\omega_n t+\phi_n) \end{bmatrix} \\
H_2 &= \begin{bmatrix} U_0\cos(\omega_0 t+\phi_0)+U_1\cos(\omega_1 t+\phi_1)+U_2\cos(\omega_2 t+\phi_2)+ \\ ....+U_n\cos(\omega_n t+\phi_n) \end{bmatrix}^2 \\
H_3 &= \begin{bmatrix} U_0\cos(\omega_0 t+\phi_0)+U_1\cos(\omega_1 t+\phi_1)+U_2\cos(\omega_2 t+\phi_2)+ \\ ....+U_n\cos(\omega_n t+\phi_n) \end{bmatrix}^3 \\
H_n &= \begin{bmatrix} U_0\cos(\omega_0 t+\phi_0)+U_1\cos(\omega_1 t+\phi_1)+U_2\cos(\omega_2 t+\phi_2)+ \\ ....+U_n\cos(\omega_n t+\phi_n) \end{bmatrix}^n
\end{aligned} \quad (3)$$

If the system is phase insensitive, the general form is defined as by carrying out simple editing:

$$\begin{aligned}
H_1 &= \begin{bmatrix} U_0\cos(\omega_0 t)+U_1\cos(\omega_1 t)+U_2\cos(\omega_2 t)+U_3\cos(\omega_3 t)+ \\ U_4\cos(\omega_4 t)+U_5\cos(\omega_5 t) \end{bmatrix} \\
H_2 &= \begin{bmatrix} U_0\cos(\omega_0 t)+U_1\cos(\omega_1 t)+U_2\cos(\omega_2 t)+U_3\cos(\omega_3 t)+ \\ U_4\cos(\omega_4 t)+U_5\cos(\omega_5 t) \end{bmatrix}^2 \\
H_3 &= \begin{bmatrix} U_0\cos(\omega_0 t)+U_1\cos(\omega_1 t)+U_2\cos(\omega_2 t)+U_3\cos(\omega_3 t)+ \\ U_4\cos(\omega_4 t)+U_5\cos(\omega_5 t) \end{bmatrix}^3 \\
H_n &= \begin{bmatrix} U_0\cos(\omega_0 t)+U_1\cos(\omega_1 t)+U_2\cos(\omega_2 t)+U_3\cos(\omega_3 t)+ \\ U_4\cos(\omega_4 t)+U_5\cos(\omega_5 t) \end{bmatrix}^n
\end{aligned} \quad (4)$$

Except for very special conditions, it is not used much after the fifth harmonic. A multi-tone input non-linear system has many terms at its output. The general decomposition of these terms is:

a) Constants,

b) Full harmonics

c) Difference frequency components other than the carrier (IMD frequencies used),

d) The difference with the carrier is frequency components (unused IMD frequencies).

These difference frequency components;

a) Constants are not used,

b) Full harmonics are not used,

c) Difference frequencies obtained from other tone input signals other than the carrier may consist of IMD1, IMD2, IMD3, IMD4, IMD5 and higher terms. All of these difference frequency components are intermodulation (IMD) frequency components. IMD frequency difference components are used in fiber optic communication systems.

d) Carrier and other harmonic difference frequency components cannot be used today. There may be different reasons for this. We think that these unused difference frequency components can be made usable. IMD difference frequencies produced from first, second, third, fourth and fifth harmonic terms can be used in IMD applications. In some non-linear systems, the amplitudes of the IMD difference frequency terms derived from the third and fourth harmonics may be larger than the first harmonic amplitude [11]. Therefore, it should be taken into account

It is generally used up to the third harmonic in IMD communication systems. However, IMD frequencies consisting of 3, 4, and 5th harmonics can also be used if appropriate conditions are created. The general form of IMD frequency components is defined as follow

For third harmonics,

$$\left(\pm 3\omega_0 t \pm A\omega_1 t \pm B\omega_2 t \pm C\omega_3 t \pm D\omega_4 t\right), \quad A,B,C,D = 1,2,3,4,5 \tag{5}$$

For fourth harmonics,

$$\left(\pm 4\omega_0 t \pm A\omega_1 t \pm B\omega_2 t \pm C\omega_3 t \pm D\omega_4 t\right), \quad A,B,C,D = 1,2,3,4,5 \tag{6}$$

For fifth harmonics,

$$\left(\pm 5\omega_0 t \pm A\omega_1 t \pm B\omega_2 t \pm C\omega_3 t \pm D\omega_4 t\right), \quad A,B,C,D = 1,2,3,4,5 \tag{7}$$

Equations (4), (5) and (6) represents the passing A, B, C and D harmonic coefficients. The generalized form of all IMD frequency components can be defined as:

$$\begin{bmatrix} \pm\left(R\omega_0 t + \phi_0\right) \pm \left(A\omega_1 t + \phi_1\right) \pm \left(B\omega_2 t + \phi_2\right) \\ \pm\left(C\omega_3 t + \phi_3\right) \pm \left(D\omega_4 t + \phi_4\right) + ... \end{bmatrix} > 0 \tag{8}$$

$$and \ R, A, B, C, D... = 1,2,3,4,5...,$$

Equation (7) represents the passing R, A, B, C and D harmonic coefficients. The difference has been made into a general form for frequency analysis and the result must be positive greater than zero for it to be meaningful. Equation (8) is theoretically defined. It is not technologically possible to generate negative frequency in real physical systems. For all difference frequencies to have physical meaning, the result must be positive greater than zero. In this case, the general form of the equation is

$$\begin{bmatrix} -\left(R\omega_0 t + \phi_0\right) - \left(A\omega_1 t + \phi_1\right) - \left(B\omega_2 t + \phi_2\right) - \\ \left(C\omega_3 t + \phi_3\right) - \left(D\omega_4 t + \phi_4\right) - ... \end{bmatrix} < 0$$

$$and \ R, A, B, C, D... = 1,2,3,4,5..., \tag{9}$$

## 3. ALTERNATIVE PHASE IMD SYSTEM

The intermodulation distortion (IMD) frequency components are generally derived from the harmonic generation of multi-tone input non-linear systems. The classification of difference frequencies can basically be divided into two groups. Many of the 1st group IMD difference frequency components are still used today. There is no carrier frequency in these difference frequencies. As seen in Figure.1, it only consists of the difference frequency obtained from other input signals. The IMD used today consists of frequency components

The second group alternative difference frequency components are the difference frequencies where the carrier and other input signals may also be present. These difference frequency components are not used today due to various reasons. That is today's engineering problem. Here are a few examples for these: There are many terms such as $(\omega_o + \omega_1)$, $(\omega_o + \omega_2)$, $(\omega_o + 2\omega_2)$, $(\omega_o + \omega_1 + \omega_2)$, $(\omega_o + \omega_1 + \omega_2)$, $(\omega_o + \omega_1 - \omega_2)$, $(\omega_o + 2\omega_1 + \omega_2)$, $(\omega_o + 2\omega_1 - \omega_2)$, $(\omega_o + 3\omega_1 + \omega_2)$ and $(\omega_o + 3\omega_1 - \omega_2)$. These frequency components can vary depending on the number of input tones. Semiconductor electronic devices, whose amplitudes produce non-linear harmonics, can vary depending on the non-linear degree. For example, the number of components of frequency harmonics produced by the 4-input and fourth-order nonlinear system is more than 2900. These frequency components are only the first group difference frequency components. Only this group is used in IMD applications. The other second group difference frequency components are not used today due to technological reasons or cannot be used due to engineering problems. These alternative frequency components are carried reluctantly within the transmission medium. In our proposal, we propose a new approach and technique to make these unused difference frequency components usable. The block structure of this new system approach can be seen in Figures 2-5.

In communication systems, if the cables used as transmission media are copper or fiber cables, the bandwidth of the system is limited due to physical reasons. Increasing the bandwidth of these cable systems is also very limited with today's technology. Today, many different modulation techniques are being developed, tested and used. For this, we recommend using unused harmonic components existing in transmission lines. Fig. 2 shows the block system of the first group IMD frequency components used today. Fig. 3 shows the block system structure for the use of the second group of alternative IMD frequency components.

The difference of this system from group-I is the phase modulation of alternative IMD frequency components or the use of a different modulation technique. It is suggested here that each alternative IMD frequency

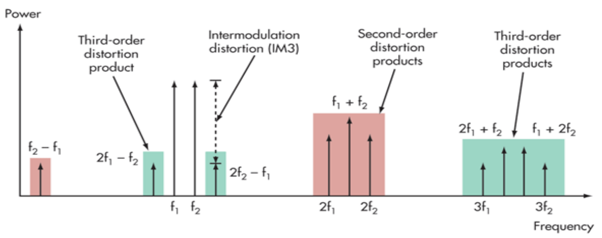


**Figure 1.** Some IMD difference frequency components used today can be seen.

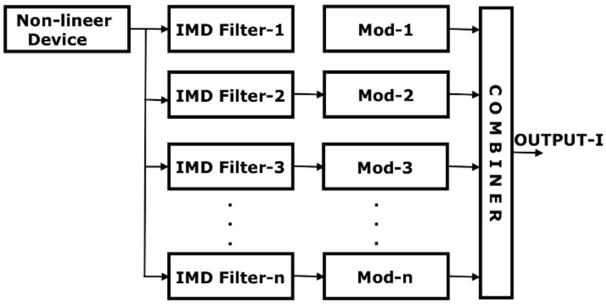


**Figure 2.** 1st Group modulation operations of the transmitter system.

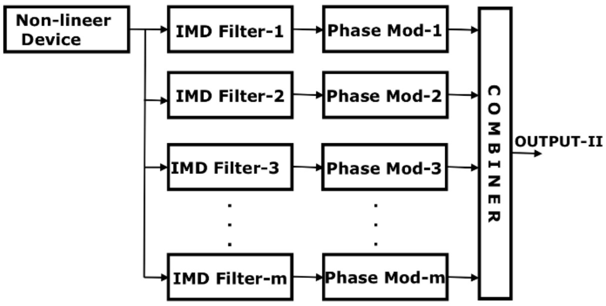


**Figure 3.** Group II modulation processes of the Transmitter System.

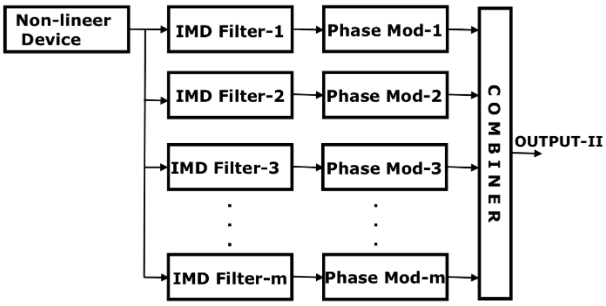


**Figure 4.** Block structure of the system receiver.

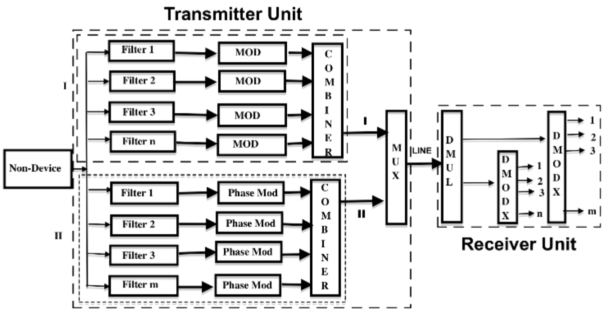


**Figure 5.** Block structure of the whole system.

component is used by modulating in different phases. Thus, the same process is performed for each alternative IMD frequency component. Then, by adding a different protocol for these alternative IMD frequency components, a distinctive feature is added. In the next operations, output-2 is obtained with a combiner as seen in Fig. 3. The feature of the combiner in Fig. 3 is that it has the ability to add protocols as group-1 and group-II within each IMD frequency component while combining. With this protocol, both groups of IMD frequency components can be easily separated from the others. We do not think that this will be a problem for today.

On the other hand, Fig. 4 shows the block structure of a new combiner. The feature of this combiner is that it combines the output-I and output-II and makes it suitable for the transmission line. Thus, it is transmitted after the appropriate conditions to be transmitted in the transmission medium of the communication system are created. In this system, normal IMD conflicts (output I) and alternative IMD frequency components (output II) are combined to obtain a single output. This output is also given to the transmission line and transmitted from the infrastructure of the system in the form of a combined signal. On the other receiver part of the transmission line, there is a separator block system. The main function of this system is to separate the entries primarily being group-I and group-II. Two separate IMD frequency components separated as group-I and group-II are separated again. The number of alternative IMD frequency components is more than 5000, especially for systems with 4 or more signal inputs with multi-tone inputs. The sensitivity of the phase detectors to be used should be selected in accordance with the number of alternative difference frequencies used. The other alternative is to separate each IMD component by combining it with a different protocol. In this case, there is no need for phase modulation. The separation problem is solved only by software.

## 5. DISCUSSIONS AND CONCLUSION

In this study, a theoretical and systematic study has been carried out to increase the bandwidth of sub-carrier communication systems. As an application example, an alternative proposal has been made to solve the bandwidth problem of fiber optic, wired and wireless communication systems. Considering that all real physical systems produce non-linear harmonic distortion, we think this approach would be realistic to increase bandwidth. To increase the bandwidth of sub-carrier networks, IMD-phase intermodulation technique can be an alternative solution proposal. In this alternative approach, it is thought that if the phase shift is very small, very large bandwidth will be obtained by making limited changes in the infrastructure of the networks. In this case, it is technically possible to use all alternative IMD difference frequencies in multi-tone input network systems, and there is no theoretical limitation. Practically, there may be a physical limitation regarding the energy transfer of the cable structure used in the infrastructure. This problem is only a current technological limitation. If this limitation is exceeded, all frequency components can be used. This second group of alternative IMD difference frequency components can be made by using a separate protocol for each frequency component by adding a distinctive feature from other IMD difference frequencies with software, or using both methods together can do it. If the protocol is used as the distinguishing feature, it may not be necessary to do

IMD-phase modulation. Thus, in both cases, it can make a great contribution to the solution of the bandwidth problem of the networks. The main problem with the unused IMD frequency components is the filtering for the frequency and the close amplitudes. When this problem is resolved, unused IMD difference frequency components become available. A proposal has been made to the bandwidth problem of commercial networks.

The proposed method can be widely used in communication systems with multi-input and multi-output techniques, analog, digital and fiber optic network systems. However, they take very different names according to the modulation technique. The main reason for using multi-input and multi-output techniques is to increase the bandwidth of the system and to send more information per unit time on the same transmission line. The other technical meaning of bandwidth is to make more commercial gains by using the same infrastructure of the communication system. While increasing this bandwidth provides gain for optimal limit values, it can slow down the communication system if the optimal bandwidth value is exceeded. Another advantage of these techniques is that they make a great contribution to the economic sustainability of communication network systems.

## DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

## AUTHORS' CONTRIBUTIONS

**Abdurrahman HAZER:** Wrote the manuscript and contributed at all stages of the article.

**Remzi YILDIRIM:** Perofrmed the experiments and analyse the results. Wrote this manuscript.

## CONFLICT OF INTEREST

There is no conflict of interest in this study.

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