Analytical Comparison of Various Detection Techniques for SAC-based OCDMA Systems: A Comparative Review

Teena Sharma and M. Ravi Kumar

Abstract Spectral amplitude coding-optical code division multiple access (SAC OCDMA) is the most popular technique due to its suitability in asynchronous environment with efficient codes and detection techniques. In this paper, we have presented a comparative analysis of various detection techniques utilized for SAC-based OCDMA to improve the system performance and minimize the noises. Each detection technique has a different architecture for detection of information and based on that, amount of multiple access interference (MAI) is eliminated. Further, its selection criteria relies upon multiple factors such as type of optical code and particular application area. In some of the optical codes, very less overlaps in spectra of various clients are present due to its ideal cross-correlation properties among each user; therefore, in this case used detection technique carries fewer optical and electrical components. This reduces MAI to a considerable extent. Furthermore, proposed idea of analyzing various detection technique suggested use of particular detection techniques based on specific application and system parameters.

Keywords OCDMA · SAC OCDMA · Cross-correlation code · Detection · Multiple access interference

1 Introduction

In OCDMA framework, spectral amplitude coding (SAC) technique got more consideration due to usages of high auto-correlation and low-value cross-correlation-based codes which deals with multiple access interference (MAI) well. Further, simple encoders and decoders consisting of fiber bragg grating (FBG) structures provides easier spectral encoding and decoding when compared to high-speed electronic

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circuitry utilized in spectral phase decoding [1]. It uses inexpensive incoherent sources of light for spectral encoding [2]. Multiple detection techniques such as direct detection and complementary subtraction detection techniques are utilized at the receiver [3, 4]. Therefore, using codes with best possible auto-correlation and cross-correlation properties, MUI and PIIN are eliminated to a certain extent. Further, detection techniques plays an important role in elimination of MAI in SAC OCDMA by removing overlapping chips [5].

For SAC system, optical communication channel may be either fiber optic or wireless free-space optics. We have focused on detection techniques those utilizing 1-dimensional SAC code. Optical codes should have best cross- and auto-correlation properties to minimize MAI and probability of error. Moreover, codes should possess properties such as flexibility in code weight selection, low bit error rate (BER) and high level of security. The code construction algorithms should be easy and simple, and it should result in less complex and cost-effective architecture implementation [6, 7]. With the code design, selection of detection technique as per the optical code properties plays major role in achieving better quality of signal.

Aim of developing good codes can be fulfilled by designing code families, supporting large cardinality with optimal code length so that bandwidth requirement can be minimized and that can also provide flexibility in addressing code sequences [8]. Further, SAC methods have flourished as successful schemes for local area network (LAN), fiber-to-the-home (FTTH), and multimedia applications especially triple play services as it makes use of different constant-weight and variable-weight code families, each with different properties.

In direct detection (DD) technique (Fig. 1), each received signal consists of non-overlapped spectral components, which represented a unique method for individual user required for diode detector [9]. At receiver side, FBGs as filter in combination with single photo diode are used for detection of non-overlapping optical pulses. PIIN is eliminated on detecting non-overlapping spectra [10]. Moreover, single photo

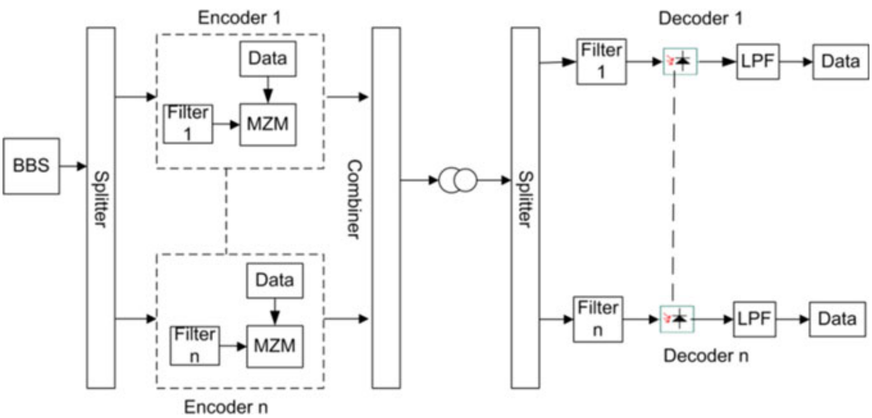

Fig. 1 SAC-OCDMA system architecture using direct detection technique

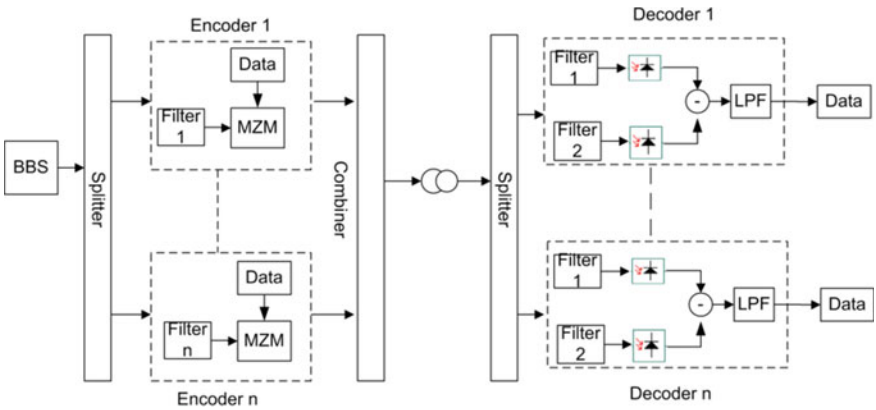

Fig. 2 SAC OCDMA system architecture with balanced detection technique

diode reduces receiver complexity and provides improvement in BER performance. In DD technique power splitters, two PIN diodes and subtractor are not required at the receiving side likewise complementary subtraction (CS) or balance detection (BD) technique [11]. System implementation cost is lesser for such system due to use of less components. FBGs are used for encoding and decoding at transmitter and receiver side for balanced and DD techniques.

In BD technique, decoder's output data are further transmitted to two photodiodes (PD1 and PD2), and via an electrical detection process which futher involves subtraction of overlapping chips, integration, sampling of data, and threshold detection to recover the original data bits (Fig. 2). In this process, MAI could be removed completely with the help of balanced photo-detection process by subtraction of overlapping chips [12].

The remaining paper is compiled as follows: Sect. 2 discusses the selection criteria of detection techniques. Types of detection techniques are discussed in Sect. 3 with seven Sects. 3.1–3.7 consists of receiver design for each detection method. Section 4 presents comparative analysis of most popular detection techniques. The study is summarized in Sect. 5.

2 Selection Criteria of Detection Techniques

Detection of transmitted signals is quite challenging in presence of system noises and many other performance-affecting parameters for optical CDMA systems. To maintain performance of optical system, detectors should be designed according to code-specific manner to easily decode the transmitter information. Detection techniques placed at the receiver end can effectively suppress MUI if the code is not a zero correlation code. So far, two detection techniques are quite popular. At receiver side of SAC system, either of the two photodiodes is utilized in balanced mode to subtract MAI and either one subtractor or single photodiode is used for detection of optical signals. First technique is called complementary subtraction or balance detection and second one is called direct detection (DD) technique.

DD detection is generally used with zero cross-correlation codes but can be used for variable cross-correlation codes depending on specific application [13, 14]. In CS, both originally transmitted signal and the compliment of the signal are decoded and compared. Finally, an auto-correlation function is generated, which is useful for retrieving original signal. Cost and complexity of the system hardware increase due to increase in optical and electrical components. Only non-overlapping chips are decoded in the process of DD technique. Therefore, reduced number of components is required. Advanced detection techniques based on operation of logic gate AND named as AND subtraction and modified AND detection technique is introduced in [15], which improved system performance due to reduced number of FBGs utilized in encoding and decoding process.

3 Types of Detection Techniques

3.1 Complementary Subtraction Detection or Balance Detection

CS detection technique has been the most commonly used detection technique (Fig. 3). The two different received signals are modulated with data and multiplexed and transmitted over fiber. Combined signals are divided into two different complementary branches of spectral chips at the receiver.

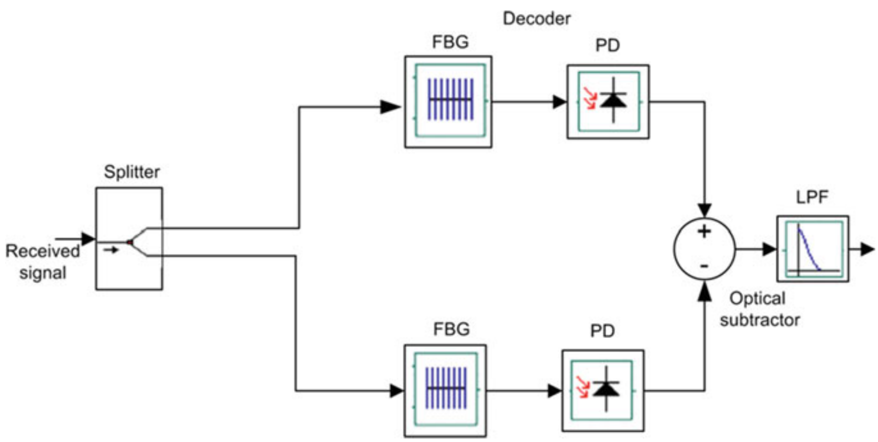

Fig. 3 Complementary subtraction detection technique based SAC OCDMA receiver

A subtractor placed at output finds the correlation difference by subtracting signals received from two branches. The zero value of subtractor output means no cross-correlation between user data so no overlapping. Moreover, the complementary detection technique can be used for the codes those have fixed value of cross-correlation. The drawback of balanced detection is that for SAC systems, most of the codes are generated by using code mapping techniques for increased number of subscribers, but due to mapping, cross-correlation is not always fixed in this case. Consequently, this detection technique does not provide accurate results [15].

3.2 Single Photodiode Detection (SPD) Technique

SAC OCDMA receiver with SPD technique is shown in Fig. 4. There are two decoders in this case: The first one has identical filter spectral response matching with intended encoder, and another is subtractive decoder or s-decoder which cancels signals with mismatched signature code sequences or interferers [16]. Frequency bins coming from different interferers are present in s-decoder. Obtained s-decoder output is zero power in case of active user or equal to cross-correlation power for interfering clients. fiber bragg gratings (FBGs) have been used to perform decoding and encoding operations as well as to compensate dispersion. Subtraction output is either equal to code weight power for active client or zero power for interferers. Therefore, before conversion of signals to the electrical domain, interference gets cancelled in the optical domain which further removes MAI and PIIN effects in the optical domain. However, two interference signals differed slightly from each other at the optical subtractor and resulted into less optical power reception at photodiode.

The use of single photodiode becomes possible due to suppression of interference signals within optical domain. Shot noise generated at the receiver side and optical-to-electrical conversion processing are reduced with the help of this technique. Any fixed in-phase cross-correlation code could be used to implement SAC with SPD

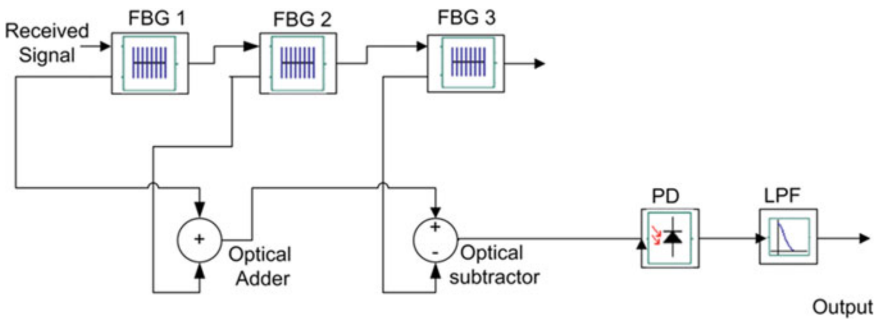

Fig. 4 SPD technique-based SAC OCDMA

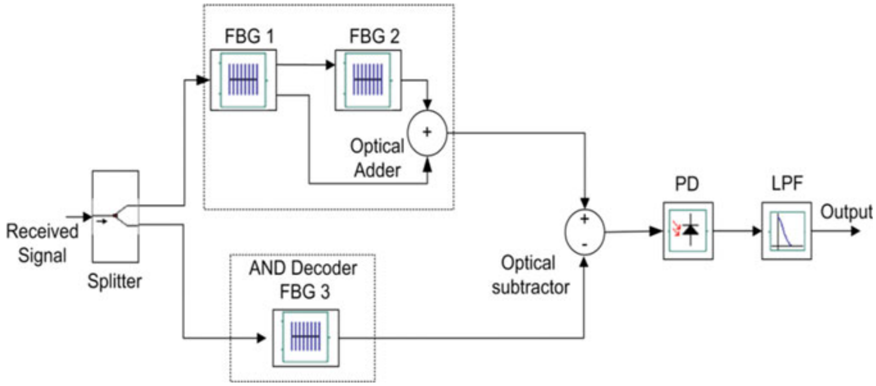

Fig. 5 SAC OCDMA receiver based on AND subtraction detection technique

detection just by simply modifying spectral distribution of s-decoder, which basically depends on the SAC codes structure [17].

3.3 AND Subtraction Detection

Incoming signal is divided into two parts: First part is decoder with same filter structure similar to encoder and second part of the decoder has AND filter structures [18]. Signal between wavelengths is compared by logic AND to detect the same wavelength or overlapping chip. In order to subtract the overlapping code from the intended code sequence, a subtractor is placed before the photo diode. Therefore, overlapping chips are eliminated and photo diode only receives the desired information. Therefore, it can successfully eliminate MUI just like complementary detection but only for the codes having fixed cross-correlation. It provides significant improvement in transmission distance or higher data rates with increased number of subscribers (Fig. 5).

3.4 Modified AND Subtraction

Previous studies showed that the performance of modified-AND subtraction detection technique is better for SAC OCDMA systems when compared with AND subtraction and complementary subtraction techniques [19]. The modified-AND subtraction could reduce the effects of both PIIN and MAI. However, it utilizes similar number of filters as used by AND subtraction and less number of filters

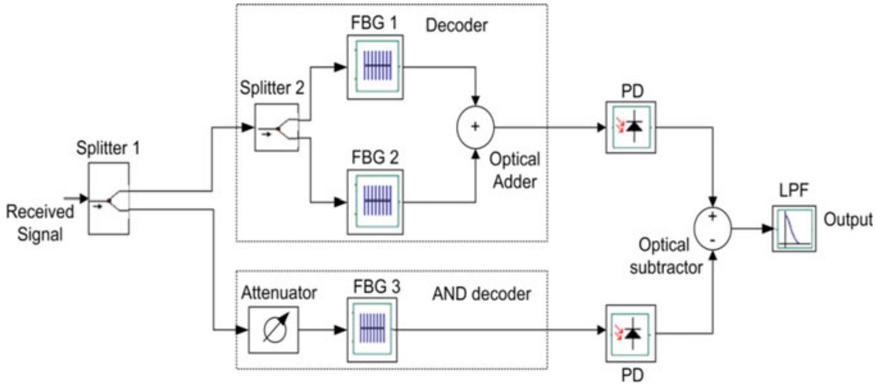

Fig. 6 Modified-AND subtraction detection technique-based SAC OCDMA receiver

when compared with complementary subtraction technique. This technique basically divides the decoded signals spectrum by utilizing a parallel structure of filters at the decoder end.

The SAC OCDMA receiver showed that the received optical signal is split by splitter 1 into two parts. First part is split into the upper decoding branches, whereas the second part is split to the AND decoder by using an attenuator. The attenuator fortified that for each inactive user, the interference signal showed an equivalent power incident on individual photo-detectors (Fig. 6).

The decoder showed a matched spectral response with active user, whereas AND decoder showed the overlapped bins from different interferers. AND operation among active user and interferers could be mathematically represented by these overlapped bins. Two photodiodes such as PD and subtractive-PD are used to compose the photodetector and in order to provide a differential output signal between both decoded signals; they are electrically connected in opposition.

3.5 XOR Subtraction Detection

XOR technique is used to suppress MUI for the code signature sequences which have in-phase cross-correlation either 0 or 1, i.e., for the codes which do not have fixed cross-correlation. This technique is used with the code sequences which are less rigorous IPCC constraints. By using this technique, desired signal spectral chips which are in optical form would be filtered; therefore, no MUI between codes is obtained. The reason being that code properties that possess the maximum cross-correlation between any two code words is 1. This results in suppressed PIIN noise at the receiving end [20]. Thus, system performance is improved by using XOR detection scheme. Advantage of XOR over any other detection technique is that any number of subscribers can be filtered out whether they have fixed cross-correlation

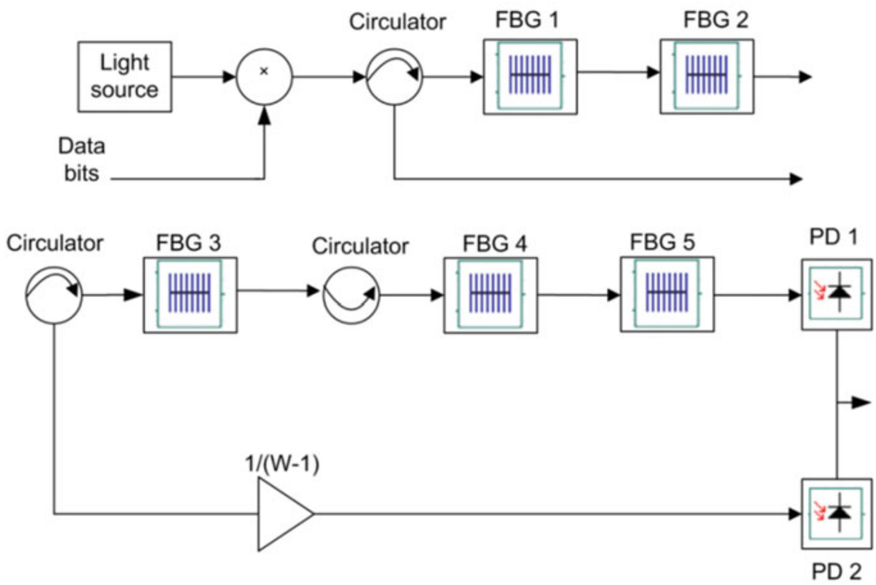

Fig. 7 XOR subtraction detection technique-based SAC OCDMA transmitter/receiver

or not. Thus, code freedom can be obtained. System performance is improved due to elimination of MUI, intensity noise, and probability of error. The disadvantage of XOR over AND detection is that hardware complexity of overall system is increased slightly. Thus, a trade-off can be set between the code freedom and hardware complexity for better performance.

SAC system with XOR detection technique is represented in Fig. 7 which consists of an ON–OFF shift keying modulator to modulate the desired user data. The modulated signal is then sent to FBGs, and desired user's chip is being attributed with some specific set of wavelengths. FBGs position depends on the chip value, and it is used for only for chip "1." Its decoder is based on same idea as complementary technique which is consisting of FBGs set with the original weight and its complementary part. Finally, received signal is passed to photo detector. Only codes matched with desired receiver are send to both the photo diodes to get the desired output, and codes that are mismatched pass without getting detected. Moreover, the system performance is highly improved when compared to the existing detection techniques for suppressed MAI and PIIN due to filtering of only wanted chips in the optical domain.

3.6 NAND Subtraction Detection

The procedure for obtaining cross-correlation for two-coded sequences is same for AND and NAND detection techniques. MAI could also be removed for both the

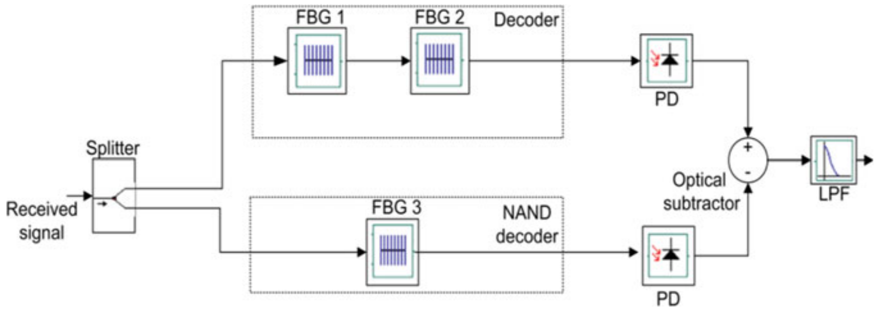

Fig. 8 Receiver based on NAND subtraction detection technique

techniques effectively. However, NAND-based detection gives extra weights during subtraction-based detection procedure. These extra weights result in increased signal power. NAND-based detection scheme results in increased signal-to-noise ratio, and thus, improved system performance for SAC systems. In this technique, only desired optical spectral chip is filtered, and thus, the resultant signal is free from any MUI and PIIN is suppressed at the receiving end. By following all the factors, it can be stated that SAC OCDMA performance is enhanced with NAND based detection [21].

Figure 8 shows that the NAND subtraction received signal has been divided into two blocks. First block decoded by an optical filter FBGs and the same structure as that used in the encoder, whereas the second block decoder also called NAND decoder has a structure of NAND filter [22]. NAND decoder is based on NAND operation of NAND logic and not basically a NAND gate. Overlapping wavelengths or interference from other users are subtracted in optical subtractor to eliminate MAI and finally detected by two photo detectors. Receiver complexity and system cost increase due to subtraction technique, but it provides accuracy in solving MAI-related issues by making use of the complete weight present in the user code sequence and thus suppress MAI. In the NAND subtraction detection, larger code weights are generated which causes signal power to increase thus results in high SNR and improved system performance when compared to AND, complementary, and XOR subtraction.

3.7 Direct Detection Technique

DD technique is shown in Fig. 9. It is applicable for codes with zero cross-correlation properties only. Signals can be detected from clean chips only, and no subtractor is required. One pair per user of detector and decoder is required when compared with CS detection process, which used two pairs per user [23]. Thus, numbers of components are reduced in this process. In addition, receiver is cost effective, simple, and reliable due to implementation of DD technique at receiver side of SAC OCDMA system. Number of PIN detectors are just half of that used in complementary detection

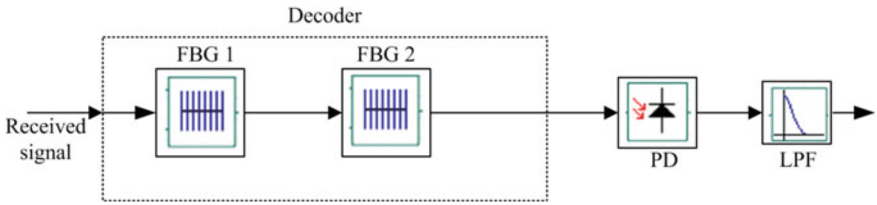

Fig. 9 Receiver based on direct detection technique

process. Moreover, DD technique effectively reduces PIIN due to presence of lesser number of chips at the photo detector [24–27].

4 Comparative Analysis of Detection Techniques

We considered two different OCDMA sequences $X = (1100)$ and $Y = (0110)$, and these sequences are modulated using user data and multiplexer. Based on type of detection method, correlation difference between spectral chips is calculated and is illustrated in Table 1.

5 Conclusion

In this paper, we have performed a comparative analysis of various detection techniques utilized in SAC-based OCDMA system. Each detection technique-based receiver design is compared with existing techniques. Moreover, for each technique, computation of cross-correlation is done by utilizing two different OCDMA code sequences. This study further provides knowledge of particular detection technique based on specific application. From the analysis, we can say that each detection technique provides a different implementation cost based on number of components utilized and each technique covers a different fiber distance. However, the DD technique is mostly preferred among all the techniques as it uses fewer photo detectors, power splitters, and subtractors; therefore, it provides lowest cost and less complex receiver architecture when compared to existing detection methods. DD provided better performance in terms of PIIN elimination by detecting clean chips only; thus, system performance is improved in this case. Furthermore, full code spectra are transmitted to recover the signature sequence resulting in higher received signal power when DD technique is used.

Table 1 Comparison of various complementary, AND-, NAND-, and XOR-based detection techniques

	Complementary subtraction				NAND subtraction				AND subtraction				XOR			
	λ_1	λ_2	λ_3	λ_4	λ_1	λ_2	λ_3	λ_4	λ_1	λ_2	λ_3	λ_4	λ_1	λ_2	λ_3	λ_4
X	1	1	0	0	1	1	0	0	0	0	1	1	0	0	1	1
Y	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0
	$\theta_{XY} = 1$				$\theta_{XY} = 1$				$\theta_{XY} = 1$				$\theta_{XY} = 1$			
	$\theta_{\overline{XY}} = 0011$				$\theta_{\widetilde{XY}} = 0011$				$X \,\&\, Y = 0010$				$X \oplus Y = 0101$			
	$\theta_{\overline{XY}} = 1$				$\theta_{\widetilde{(XY)Y}} = 1$				$\theta_{X \,\&\, Y} = 1$				$\theta_{X \oplus Y} = 1$			
Z	$Z = \theta_{XY} - \theta_{XY} = 0$				$Z_{\mathrm{NAND}} = \theta_{XY} - \theta_{\widetilde{(XY)Y}} = 0$				$Z_{\mathrm{AND}} = \theta_{XY} - \theta_{(X \,\&\, Y)Y} = 0$				$Z_{\mathrm{XOR}} = \theta_{XY} - \theta_{(X \oplus Y)Y} = 0$			

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