# The Analysis of Shift Alternative Repeated Unequally Spaced Channels Allocation for DWDM System

C. Srinuan and S. Noppanakeepong

***Abstract*—This paper proposes the new method to improve the conventional techniques in the channel allocations in order to reduce transmission loss in the case that a large number of channels are in close proximity to each other. This phenomenon, called Four-Wave Mixing (FWM), can be observed in the case of Dense Wavelength Division Multiplexing (DWDM) which is the cause of transmission loss due to the nonlinear characteristic of the fiber. The channel allocations that can be utilized to resolve this problem are Equally Spaced (ES), Equally Repeated Unequally Spaced (ERUS) and Base-unit Repeated Unequally Spaced (BRUS). This paper presents the new technique of the channel allocation called "Shift alternative repeated unequally spaced (SARUS)" to avoid the Four-Wave Mixing. From the simulation results, the new proposed technique can decrease an average FWM efficiency from -28.19dBm to -32.07dBm and reduce BER from -19.7dBm to -25.1dBm. Furthermore, the number of channels has been increased to 43 channels in DWDM transmission system (C–band). These results indicate that SARUS has a lower FWM efficiency than BRUS and other above mentioned techniques.**

***Index Terms*—Dense wavelength division multiplexing, four wave mixing, nonlinear, shift alternative repeated unequally spaced, channel allocation.**

## I. INTRODUCTION

At the present time, optical network capacity has been increasing due to Wavelength Division Multiplex (WDM) system. DWDM is the key element that ensures the effective operation of the Internet and telecommunication traffic in wide-area and local-area network. When long-distance transmission system is required, the level of launched optical power increases and fiber nonlinearity becomes prominently increased. This leads to interference, distortion, and excess attenuation of the transmitted signals which induces system degradations. There are several nonlinear effects in WDM systems, such as stimulated raman scattering (SRS), stimulated brillouin scattering (SBS), self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). FWM impairments become increasingly more severe in DWDM system. The DWDM light source multiplexer was used as 100GHz frequency equally spacing (ES) [1] that occurs at a very high number of FWM value. This, however, could reduce FWM value with an optical filter of DWDM de-multiplexer device for which channel allocation can be utilized. In order to design a new method in channel allocation, several research papers (RUS [2], ERUS [3], BRUS [4]) were analyzed. The new method is called "SARUS" model. Its purpose is to decrease FWM without the need to depend on any optical filter device. The result of this research indicates the lower FWM and BER values.

This simulation was constructed under the conditions of the generated wavelength follows in C-band (1529.55-1560.61 nm) EDFA in ITU-T G.694.1 [5]. From this research, it is discovered that SARUS model can effectively decrease FWM and BER. In this paper, the frequency spacing is specified higher than 50GHz due to the limit of optical multiplexer and de-multiplexer device [6]. The parameters in this simulation are as follow: Dispersion Shifted Fiber (DSF) is specified at the length ($L$) of 80km, fiber loss coefficients α of 0.2dB/km, derivative dispersion coefficient ($dD/d\lambda$) of 0.06ps/km/nm$^2$, effective core area ($A_{eff}$) 50 $\mu m^2$ and APD has quantum efficiency ($\eta$) of 80% [7].

## II. FUNDAMENTAL OF ANALYSIS

### A. Four-Wave Mixing

A light frequency $f_{FWM}$ of FWM frequency, which is generated by third-order non-linear affected to three signal light frequencies $f_i$, $f_j$ and $f_k$ show on Fig. 1 and as follows

$$f_{FWM} = f_{ijk} = f_i + f_j - f_k (i, j \neq k) \tag{1}$$

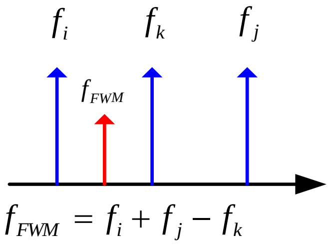

Fig. 1. FWM between frequencies spaced that nonlinear effect arising from a third-order optical nonlinearity.

Since the primary concern is FWM, self-phase modulations, cross-phase modulations, and waveform degradation due to bandwidth limit are ignored. The total number of FWM frequencies $M$ generated in an optical DWDM system of channels $N_c$ is illustrated is (2) and Fig. 2 shows FWM effect from 3 channels.

$$M = \frac{1}{2}(N_c^3 - N_c^2) \tag{2}$$

The generation of FWM lights causes performance degradation in two ways, namely, by depleting the power of transmitting signal lights and by interfering with the lights,

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C. Srinuan and S. Noppanakeepong are with the Telecommunication Engineering Department, Faculty of Engineering, King Mongkut's of Technology Ladkrabang, Bangkok, Thailand (e-mail: chollate@tot.co.th, knsuthic@kmitl.ac.th).

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which have the same frequencies as the FWM lights.

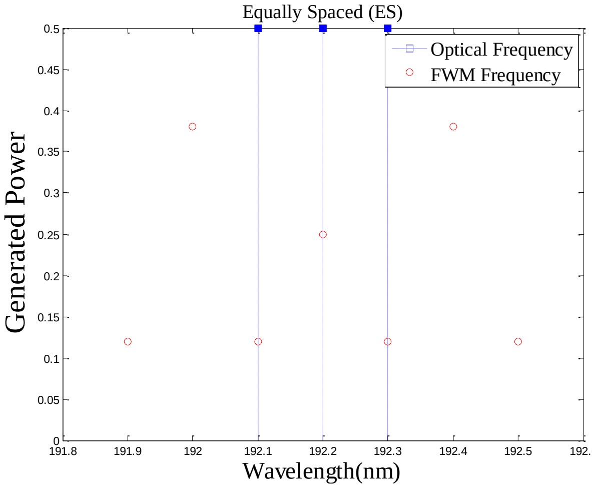

Fig. 2. FWM effect from channel allocation of ES.

The total power generated at frequency $f_m$ can be expressed as a summation [8], [9]

$$P_{total}(f_m) = \sum_{f_k = f_i + f_j - f_m} \sum_{f_j} \sum_{f_i} P_{FWM}(f_{ijk}) \tag{3}$$

The output power $P_{FWM}$ of FWM product is given by [8], [9]

$$P_{FWM}(f_{ijk}) = \frac{1024\pi^6}{n^4 \lambda^2 c^2} \left( \frac{d_{ijk} \chi^{(3)} L_{eff}}{A_{eff}} \right)^2 P_i P_j P_k e^{-\alpha L} \eta_{ijk} \tag{4}$$

where $P_i$, $P_j$ and $P_k$ represent the input power of frequencies $f_i$, $f_j$ and $f_k$, respectively, $P_{FWM}$ is the power of the light-wave from FWM at the frequency $f_{FWM}$, $n$ is the fiber refractive index, $\lambda$ is the wavelength, $c$ is a velocity of light in a vacuum, $A_{eff}$ is the effective core area of the fiber, $\alpha$ is the fiber loss coefficients, $L$ is fiber length, $d_{ijk}$ is the degeneracy factor ( $d_{ijk}$ =3 for $i = j$ , $d_{ijk}$ =6 for $i \neq j$ ), and $\chi^{(3)}$ is the third-order nonlinear susceptibility. The FWM efficiency $\eta_{ijk}$ is given by [8], [9].

$$\eta_{ijk} = \frac{\alpha^2}{\alpha^2 + (\Delta\beta)^2} \left\{ 1 + \frac{4e^{-\alpha L} \sin^2(\Delta\beta L/2)}{(1 - e^{-\alpha L})^2} \right\} \tag{5}$$

where $\Delta\beta$ represents the phase mismatch term which can be expressed in term of signal frequency differences [8], [9]

$$\Delta\beta = \frac{2\pi\lambda^2}{c} |f_i - f_k| |f_j - f_k| \left[ D + \frac{\lambda^2}{2c} \frac{dD}{d\lambda} \left( |f_i - f_0| + |f_j - f_0| \right) \right] \tag{6}$$

where $f_j$ , $f_j$ and $f_k$ are light frequencies of signals, $D$ is the fiber chromatic dispersion and $dD/d\lambda$ is a derivative dispersion coefficient of an optical fiber.

### B. Bit Error Rate (BER)

If the Gaussian approximation is used to describe the noise caused by FWM interference, the error probability of FWM $P_e$ for an intensity-modulated on-off keying (OOK) signal is written as [8], [9]

$$P_e = \frac{1}{\sqrt{2\pi}} \int_Q^\infty \exp\left( -\frac{t^2}{2} \right) dt \tag{7}$$

Therefore, in a DWDM system the nonlinear interaction between these frequency channels may generate interference frequency to a signal channel, and cause degradation of signal and increase bit error probability. In other words, actual noise caused by FWM is expected to be lower than the calculated results in this paper.

FWM light is detected at the receiver at the same time as the signal light, which induces the interference noise. The FWM noise power $N_{FWM}$ is written as [8], [9]

$$N_{FWM} = 2b^2 P_s \frac{P_{FWM}}{8} \tag{8}$$

$P_s$ is the signal light power at the receiver. In case of the input light power to the fiber $P_0$ , the fiber length is $L$ and fiber loss coefficients are $\alpha$ , $P_s = P_{in} e^{-\alpha L}$ . The SNR can be expressed as [8], [9]

$$Q = \frac{bP_s}{\sqrt{N_{th} + N_{sh} + N_{FWM}} + \sqrt{N_{th}}} \tag{9}$$

Since the thermal noise $N_{th}$ and shot noise $N_{sh}$ are very small, $N_{FWM}$ is the dominant factor of the denominator, thus the equation (9) can be written as [8], [9]

$$Q = \frac{bP_s}{\sqrt{N_{FWM}}} = \frac{2bP_s}{\sqrt{b^2 P_s P_{FWM}}} = \frac{2\sqrt{P_s}}{\sqrt{P_{FWM}}} = \frac{2\sqrt{P_0 e^{-\alpha L}}}{\sqrt{P_{FWM}}} \tag{10}$$

$$b = \frac{\eta e}{hf} = \frac{\eta e \lambda}{hc} \tag{11}$$

where $h$ Planck's constant, $\eta$ is quantum efficiency of the detector, and $e$ is the elementary electric charge. It is also assumed that the APD has a quantum efficiency ( $\eta$ ) of 80%.

## III. CHANNELS ALLOCATION

### A. Equally Spaced (ES)

This technique has signal light with equal frequency separations between adjacent signals, using a channel spacing = $\Delta f_c$ and number of channel =$N_c$ , a total bandwidth for ES = $B_{ES}$ is written as [3]

$$B_{ES} = (N_c - 1)\Delta f_c \tag{12}$$

Because $\Delta f_c$ is constant for each channel, a lot of FWM frequencies with $\Delta f_{FWM} = f_i$ are generated. From (1), the frequencies of FWM lights generated within a total bandwidth are always concurrent with those signals. Table I. Shows an example of ES channels allocation with the number of channels $N_C$ = 40 in C band and the frequency spacing $\Delta f_c$ = 100GHz.

TABLE I: EXAMPLE OF ES CHANNEL ALLOCATION OF ITU-T G.694.1

| **Channel** | **1** | **2** | **3** | **→** | **39** | **40** |
|---|---|---|---|---|---|---|
| **Δ*fc*(GHz)** | | **100** | **100** | **→** | | **100** |
| ***fi*(THz)** | **192.1** | **192.2** | **192.3** | **→** | **195.9** | **196.0** |

### B. Equally Repeated Unequally Spaced (ERUS)

This is a technique using spaced ($\Delta f_i$) into the before first of base unit and between each base unit. Which total bandwidth for ERUS ($B_{ERUS}$) is expressed as [3]

$$B_{ERUS} = nB_b + (n-1)\Delta f_i + B_{res} \tag{13}$$

Here, $n$ is the number of the base units, $B_b$ is the bandwidth of the base unit and $B_{res}$ is the bandwidth of additional channels.

### C. Base-Unit Repeated Unequally Spaced (BRUS)

This is a technique using spaced ($\Delta f_i = \Delta f_1, \Delta f_2, \Delta f_3$) into the before first of base unit. Which total bandwidth for BRUS ($B_{BRUS}$) is expressed as [4]

$$B_{BRUS} = \left(B_{b1} + B_{b2} + .. + B_{bn}\right) + \sum_{i=1}^{n} \Delta f_i + B_{res} \tag{14}$$

Here, $n$ is the number of the base units, $B_b$ is the bandwidth of the base unit, and $B_{res}$ is the bandwidth of additional channels. Based units are denoted as RUS in the follows. The first $B_{b1}$ is composed of channels 2-7 next $B_{b2}$ is composed of channel 8-13, the next $B_{b3}$ is composed of channels 14 – 19 and next $B_{b4}$ is composed of channels 20 – 25. Between the channels 1 and 2 are additional channels ($\Delta f_1$) and between the channels 7 and 8 are additional channels ($\Delta f_2$).

### D. Shift Alternative Repeated Unequally Spaced (SARUS)

The SARUS model is a new proposes, as shown in Fig.3. This technique channel allocation are modify from BRUS frequency allocation [1]. This is technique using spaced ($\Delta f_1$, $\Delta f_2$ , $\Delta f_3$ , $\Delta f_4$ , $\Delta f_5$ , $\Delta f_6$ , $\Delta f_7$ ) into between each alternative base unit, as shown in Fig.3. This is technique has lower the effect of Four-Wave Mixing than the conventional techniques and decrease bit error probabilities, containing higher channels, as shown in Table II. We use

$$\Delta f_1 = 51.56GHz,\ \Delta f_2 = \Delta f_1 + 1.56GHz,$$
$$\Delta f_3 = \Delta f_2 + 1.56GHz, \Delta f_4 = \Delta f_3 + 1.56GHz,$$
$$\Delta f_5 = \Delta f_4 + 1.56GHz, \Delta f_6 = \Delta f_5 + 1.56GHz,$$
$$\Delta f_7 = \Delta f_6 + 1.56GHz.$$

The Table II shown SARUS, which corresponds to Fig. 3, and the base units are 75, 50, 150, 125, 100GHz. The first $B_{b1}$ is composed of channels 2-7, next $B_{b2}$ is composed of channel 8-13, the next $B_{b3}$ is composed of channels 14 – 19, the next $B_{b4}$ is composed of channels 20 – 25, the next $B_{b5}$ is composed of channels 26 – 31, the next $B_{b6}$ is composed of channels 32 – 37 and next $B_{b7}$ is composed of channels 38 – 43. Before the first base unit, channels $\Delta f_1$ were added and between the base unit $B_{b1}$ and $B_{b2}$ are additional channels ($\Delta f_2$), between the base unit $B_{b2}$ and $B_{b3}$ are additional channels ($\Delta f_3$), between the base unit $B_{b3}$ and $B_{b4}$ are additional channels ($\Delta f_4$), between the base unit $B_{b4}$ and $B_{b5}$ are additional channels ($\Delta f_5$), between the base unit $B_{b5}$ and $B_{b6}$ are additional channels ($\Delta f_6$)and between the base unit $B_{b6}$ and $B_{b7}$ are additional channels ($\Delta f_7$). A total bandwidth for SARUS is expressed as

$$B_{SARUS} = nB_{b_{ARUS}} + \sum_{i=1}^{n} \Delta f_i + B_{res} \tag{15}$$

Here, $n$ is the number of bases units, $B_{b_{ARUS}}$ is the bandwidth of the ARUS, $\Delta f_i$ is the spacing between the base unit and $B_{res}$ is the bandwidth of addition channels.

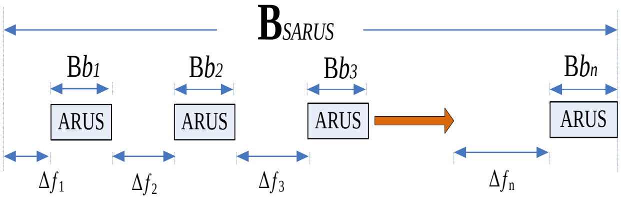

Fig. 3. Channels allocation of SARUS model.

## IV. RESULT OF ANALYSIS

The Fig. 4 shows a relation between FWM efficiency with $f_{FWM} = f_c$ and a difference in light frequencies for ES, ERUS, BRUS and SARUS. Here, $f_{FWM}$ is a frequency of an FWM light and $f_0$ is a zero-dispersion frequency, which is set at a midpoint of a total bandwidth of signal lights. It is a midpoint channel, which has the largest number of FWM frequencies among all the constituent channels—closed stars, open circles, open stars and open triangles—which are also correspond to FWM efficiencies of ES, ERUS, BRUS and

SARUS channels allocation respectively. An average number of FWM efficiency with $f_{FWM} = f_c$ for ES, ERUS, BRUS and SU-RUS is -12.03dBm, -24.5dBm, -28.19dBm and -32.07dBm, respectively. These result indicate that SARUS has lower FWM efficiencies than BRUS.

TABLE II: EXAMPLE OF SARUS CHANNEL ALLOCATION OF ITU-T G.694.1

| **Channel** | **1** | | **2** | | **3** | | **4** | | **5** | | **6** | | **7** | | **8** | | **9** | | **10** | | **11** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Δ*fc*(GHz)** | | 51.56 | | 75 | | 100 | | 125 | | 150 | | 50 | | 53.13 | | 75 | | 100 | | 125 | | 150 |
| ***fi*(THz)** | 192.1 | | 192.15 | | 192.23 | | 192.33 | | 192.45 | | 192.60 | | 192.65 | | 192.71 | | 192.78 | | 192.88 | | 192.01 | |

| **Channel** | **12** | | **13** | | **14** | | **15** | | **16** | | **17** | | **18** | | **19** | | **20** | | **21** | | **22** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Δ*fc*(GHz)** | | 50 | | 54.69 | | 75 | | 100 | | 125 | | 150 | | 50 | | 56.25 | | 75 | | 100 | | 125 |
| ***fi*(THz)** | 193.16 | | 193.21 | | 193.26 | | 193.33 | | 193.43 | | 193.56 | | 193.71 | | 193.76 | | 193.82 | | 193.89 | | 193.99 | |

| **Channel** | **23** | | **24** | | **25** | | **26** | | **27** | | **28** | | **29** | | **30** | | **31** | | **32** | | **33** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Δ*fc*(GHz)** | | 150 | | 50 | | 57.81 | | 75 | | 10 | | 12 | | 150 | | 50 | | 59.38 | | 75 | | 100 |
| ***fi*(THz)** | 194.12 | | 194.27 | | 194.32 | | 194.37 | | 194.45 | | 194.55 | | 194.67 | | 194.82 | | 194.87 | | 194.93 | | 195.01 | |

| **Channel** | **34** | | **35** | | **36** | | **37** | | **38** | | **39** | | **40** | | **41** | | **42** | | **43** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Δ*fc*(GHz)** | | 125 | | 150 | | 50 | | 60.94 | | 75 | | 100 | | 125 | | 150 | | 50 | |
| ***fi*(THz)** | 195.11 | | 195.23 | | 195.38 | | 195.43 | | 195.49 | | 195.57 | | 195.67 | | 195.79 | | 195.94 | | 195.99 |

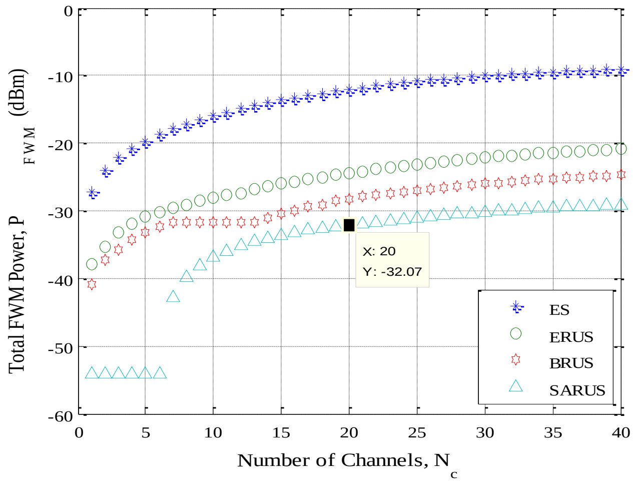

Fig. 4. Compare efficiency of FWM for channel allocation.

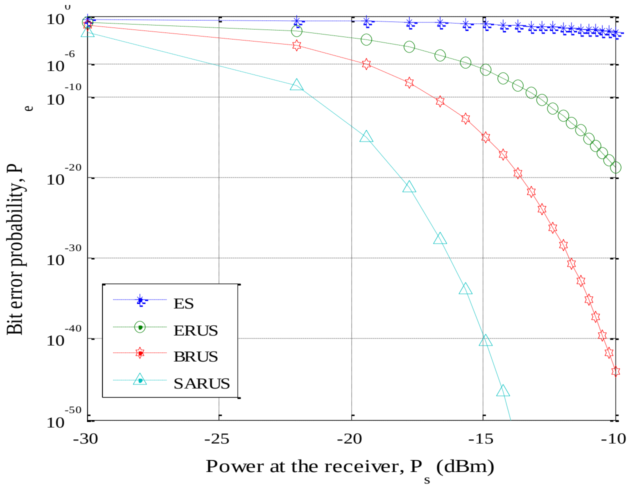

Fig. 5. Compare BER of FWM for channel allocation.

Finally, the error probability of FWM in Fig. 5 shows a relation between bit error probability of FWM $P_e$ for an intensity-modulated On-Off Keying (OOK) signal and input power per channel $P_0$. The horizontal line shows the receiver at power per channel. The vertical line shows the bit error probability of FWM. Here, closed stars, open circles, open stars and open triangles correspond to total power of FWM in ES, ERUS, BRUS and SARUS channel allocations. The receiver at power per channel $P_e$ required to achieve a BER of 10-6 for ES, ERUS, BRUS and SARUS are -5dBm, -15.7dBm, -19.7dBm, -25.1dBm, respectively. Therefore, the generated wavelength of EDFA (1529.55 – 1560.61nm) in which the bit error probability of FWM $P_e$ with $f_{FWM} = f_c$ for SARUS is lower bit error probabilities of FWM than ES, ERUS, BRUS channel allocation.

## V. CONCLUSION

From the result in Fig. 4-Fig. 5, it can be concluded that SARUS is more efficient than ES, ERUS and BRUS channel allocation methods because of the lower FWM efficiencies, and lower bit error probabilities of FWM with $f_{FWM} = f_c$. The output from DWDM light source multiplexer with equally channel spacing allocation indicates a high number of FWM value. SARUS model can reduce the FWM value and improve the operation of a DWDM light source multiplexer by not having to use an optical filter in the DWDMde-multiplexer device. As a result, mean that the SARUS model can replace the optical filter device.

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**Chollatee Srinuan** received his B.Eng. in Telecommunication engineering from King Mongkut's Institute of Technology Ladkrabang (KMITL), Thailand, in 2009. He is a candidate of M.Eng. in Telecommunication Engineering at KMITL, Thailand and is currently working at Telecom of Thailand (TOT). His research interests include optical fiber and mobile communication.

**Suthichai Noppanakeepong** received his B.Eng. and M.Eng. in Telecommunication engineering from King Mongkut's Institute of Technology Ladkrabang (KMITL), Thailand, in 1984 and in 1989, and his Ph.D. from the Tokyo Institute of Technology, Tokyo, Japan in 1996. His research interests include optical fiber communication and radio wave propagation.