Minimizing FWM Crosstalk in Millimeter-Wave DWDM Transmission over ZDSF by Unequally Spacing Channels

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Abstract - A radio-over-fiber link incorporating dense-wavelength-division-multiplexing (DWDM) transmission may suffer four-wave-mixing (FWM) crosstalk, especially when zero-dispersion-shifted fiber (ZDSF) is used. This paper presents method minimizing FWM crosstalk in such a system by unequally spacing the optical channels. We show that, by using the proposed method, FWM crosstalk can be excluded from the signal channels and the link performance can be improved.

Index Terms - Radio-over-fiber, millimeter-wave communications, unequally spaced channels, zero-dispersion-shifted fiber, four-wave mixing, dense-wavelength division multiplexing.

I. INTRODUCTION

High speed wireless accessing operating in millimeter-wave (MMW) bands has attracted a lot of interests in recent years because of the very broad band available at these frequencies [1-3]. However, due to the very high air propagation loss at MMW frequencies, the free space transmission distance of MMW’s is seriously limited under hundreds even tens meters generally, and then the connection of a central office (CO) and the remote accessing points (AP’s) meets a great challenge if direct wireless connection is employed. This issue can be addressed by radio-over-fiber (ROF), through which the AP’s and the CO is connected by optical fiber which has very low loss. This technology (ROF) is then being widely considered as means for relatively long distance MMW signals transmission, and is hopefully to be used in various systems, e.g., cellular networks, remote antenna systems, wireless LAN’s, and Intelligent Transport Systems (ITS’s) [4-5].

Also due to the high air propagation loss at MMW frequencies, the coverage area of a single cell operating in MMW bands is quite small. Therefore, in a cellular network or an ITS system incorporating MMW-ROF technologies, a great number of AP’s must be employed to provide full radio coverage, and then the fiber delivery network needs to employ lots of optical fibers to connect the AP’s to the CO’s. In order to reduce the cost of the fiber delivery network, a possible method is to utilize the current existing widely installed fibers. By doing so, a great amount of headache digging ground work also can be saved. Moreover, if the fiber delivery network employs dense-wavelength-division-multiplexing (DWDM) technology, by which many optical wavelengths can be simultaneously transmitted in a single fiber, the system cost can be further reduced [6-9]. However, some of the previously installed fibers are zero-dispersion-shifted fibers
(ZDSF), of which the dispersion at 1550 nm is zero (in order to overcome dispersion limitation for high-speed data transmission). In this case, when DWDM is employed, the phase-matching conditions of four-wave mixing (FWM) can be guaranteed and the link performance may be degraded by FWM crosstalk [10-11].

Four-wave mixing crosstalk, of course can be overcome by introducing fiber dispersion to corrupt the phase matching of the optical wavelengths, like to use non-zero-dispersion-shifted fiber (NZDSF) with about 3–6 ps/nm/km dispersion at 1550 nm. However, as mentioned above, when an installed ZDSF is utilized for transmission MMW signals, other methods minimizing FWM crosstalk are required. An effective approach is to unequally space the optical channels, so that the FWM waves can be generated other than at the signal channels [12], [13]. In [12], a frequency slots number concept is used, and then the allocation of the unequally spaced channels (USC’s) becomes a mathematic integer linear programming problem. It has been proved that there is no general and efficient method to find an optimum solution to this problem and then exhaustive computer search is needed. However, when the wavelengths number is big, the searching becomes time-consuming. Moreover, each time when channel number increases, in [12] the searching needs to restart and the channel spaces will change, meaning that the DWDM multiplexing/de-multiplexing devices need to be redesigned [14], also, the lasers central frequencies need to be rearranged. These limitations can be overcome by an evolutionary method proposed by Zhang and Sharma recently [15], by which the assignment of larger number channels can be based on smaller number channels, so that the design of the DWDM devices becomes “down-compatible”. However, the former two methods are developed for optical digital base band transmission. Since the optical power spectra of a MMW DWDM-ROF system are quite different from those of the digital base band ones, the allocation of the USC’s in such systems needs to be reconsidered.

In this paper, we present method minimizing

II. ALGORITHM OF USC ALLOCATION FOR MMW DWDM TRANSMISSION

Intensity modulation (IM) is popularly used in most of current optical digital baseband systems; also it can be employed for MMW ROF transmission. However, as intensity modulation
results in double-side-band spectrum, in which the frequency range occupied for each MMW sub-carrier transmission is $2f_m$, where $f_m$ is the frequency of the MMW sub-carrier. Thus for a large number of wavelengths MMW DWDM transmission, IM has very low spectrum utilization efficiency (SUE). If OSSB or ROSH is used, the frequency range is halved and then the SUE is improved. Moreover, if wavelength interleaving is employed, the SUE can be further improved [18]. In this research, for better SUE we assume the system employs OSSB or ROSH. The optical spectrum of OSSB is schematically shown in Fig. 1 (a), where $f_o$ is an original optical carrier and $f_o$+$f_{m}$ is an optical sideband generated in OSSB modulation. Figure 1 (b) shows the spectrum of ROSH, where the two optical spectral components at $f_1$ and $f_2$ are from a two-mode optical source and the later bears data. No matter in OSSB or ROSH, for one MMW sub-carrier transmission over fiber, we can assume an information line (for OSSB the sideband) and a reference line (for OSSB the original optical carrier) are transmitted. In following analysis of FWM products, we treat each optical signal spectral line as a single channel since the spectral lines separate by tens gigahertz.

As shown in Fig. 2, in order to unequally space the optical channels, the DWDM transmission frequency range is divided into lots of consecutive frequency slots with same width of $\Delta f$. Then when OSSB or ROSH is employed, the optical reference lines and the information lines can be expressed as $f_i=$+$f_{m}$+$\Delta f$, $i \in (1,2,3…N)$ and $f_i=$+$f_{m}$+$N\Delta f$, $i \in (1,2,3…N')$, respectively, where $f_1$ is the smallest reference line, $S_i$ is the slots number between $f_i$ and $f_i'$. The slots number is $N$ is the number of the MMW sub-carriers. Assume the MMW frequency $f_m$ is $q$ (a positive integer) times of $\Delta f$ and since $f_i=$+$f_{m}$+$\Delta f$, we have $f_m=q\times\Delta f$ and $S_i=S_i+q$. Then, an FWM wave at $f_{abc}$, where $f_{abc}=f_{a}+f_{b}+f_{c}$, $\forall a,b,c \in (1,1',2,2',3,3',\ldots N,N')$, is generated by optical spectral components at $f_{a}, f_{b}$, and $f_{c}$, can be represented by slots number $S_{abc}$, where $S_{abc}=S_{a}+S_{b}+S_{c} \forall a,b,c \in (1,1',2,2',3,3',\ldots N,N')$, $c\neq a$. The principle of USC allocation is to find a vector $(S_1, S_1', S_2, S_2', \ldots N_1, S_N, S_N')$ so that any $S_{abc}$ does not equal to any slots number, which means that no FWM wave is generated at the signal frequencies so that the FWM crosstalk is minimized.

Table 1: FWM waves in MMW DWDM-ROF transmission over ZDSF with OSSB or ROSH

<table>
<thead>
<tr>
<th>FWM waves</th>
<th>Frequency slots number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generated by three reference lines $S_{ijk}$, $\forall i,j,k \in (1,2,3…N)$, $i \neq j$</td>
<td></td>
</tr>
<tr>
<td>Generated by three information lines $S_{ijk}=S_{i}+q$, $\forall i,j,k \in (1,2,3…N)$, $i \neq j$</td>
<td></td>
</tr>
<tr>
<td>Generated by one reference line and two information lines $S_{i}$, $\forall i \in (1,2,3…N)$, $i \neq j$</td>
<td></td>
</tr>
<tr>
<td>Generated by two reference lines and one information line $S_{ijk}$, $\forall i,j \in (1,2,3…N)$, $i \neq j$</td>
<td></td>
</tr>
<tr>
<td>Generated by one reference line and two information lines $S_{i}$, $\forall i \in (1,2,3…N)$, $i \neq j$</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Optical frequency slots assignment for MMW DWDM-ROF transmission.
in Table 1, the FWM products marked by superscript (1), which are generated by optical information line at $S_i$, an optical reference line at $S_j$, and the corresponding information line at $S_k$, are bound to be generated at $S_i$, since $S_{ijk}=S_i+S_j-S_k=S_i$. It means that this type of FWM waves is bound to be crosstalk of the system at the reference lines at $f_i$ and cannot be excluded even USC is applied. Similarly, the FWM waves marked by superscript (2) are bound to be crosstalk at the information lines at $f_i$ and cannot be excluded even USC is used. While other FWM waves can be excluded from the signal frequencies, if following condition is satisfied:

$$S_{ijk}, S_{ijk} \pm q, S_{ijk} \pm 2q, S_{ijk} \neq (S_1, S_2, \ldots, S_N),$$

$$S_{ijk}=S_i+S_j-S_k, \forall i,j,k \in (1,2,\ldots,N), k \neq i,j$$  \hspace{1cm} (1)

Another restricting factor for USC allocation is from DWDM de-multiplexing. In order to minimize the linear channel crosstalk to an acceptable level in process of de-multiplexing, the space between any two adjacent channels needs to be greater than certain value. Therefore the slots number between any two adjacent channels needs to be assumed greater than (at least equal to) a minimum factor $M_f$. When the wavelengths are not interleaved for MMW DWDM transmission as shown in Fig. 2 (a), this constraint condition is given as:

$$S_i(S_i+q) \geq M_f, i \in (2,3,\ldots,N).$$  \hspace{1cm} (2)

As shown in Fig. 2. (b), when the wavelengths are interleaved, the above condition becomes:

$$|S_i-S_j| \geq M_f, \forall i,j \in (1,2,\ldots,N), i \neq j, a_k=0.1.$$  \hspace{1cm} (3)

Then the slots vector $(S_1, S_2, \ldots, S_N)$ can be allocated according to following algorithm:

If wavelength interleaving is not applied:

1. Let $S_1=0$ and $S_2=S_1+q+M_f$;
2. Check the condition given by (1) is satisfied or not, if yes go to step 3, otherwise increase $S_2$ by one and repeat this step;
3. Let $S_i=S_i+M_f$, $i \in (3,4,\ldots,N)$, apply similar process in step 2 for each $i$ till all slots numbers are assigned.

If wavelength interleaving is applied:

1. Let $S_1=0$ and $S_2=S_1+M_f$;
2. Check the conditions given by (1) and (3) are satisfied or not, if yes go to step 3, otherwise increase $S_2$ by one and repeat this step;
3. Let $S_i=S_i+M_f$, $i \in (3,4,\ldots,N)$, apply similar process in step 2 for each $i$ till all slots numbers are assigned.

The above algorithm can be schematically illustrated as shown in Fig. 3.
Table 2. Signal frequency slots numbers for 8 MMW sub-carriers at 60 GHz transmission over ZDSF employing DWDM with OSSB or ROSH.

<table>
<thead>
<tr>
<th>No.</th>
<th>Frequencies number (S, S') and assigned frequencies (Δf=1GHz, M=20, q=60)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wavelengths are not interleaved</td>
</tr>
<tr>
<td>1</td>
<td>(0,60)</td>
</tr>
<tr>
<td>2</td>
<td>(80,140)</td>
</tr>
<tr>
<td>3</td>
<td>(161,221)</td>
</tr>
<tr>
<td>4</td>
<td>(243,303)</td>
</tr>
<tr>
<td>5</td>
<td>(326,386)</td>
</tr>
<tr>
<td>6</td>
<td>(410,470)</td>
</tr>
<tr>
<td>7</td>
<td>(495,555)</td>
</tr>
<tr>
<td>8</td>
<td>(581,641)</td>
</tr>
</tbody>
</table>

Table 3. Assigned frequencies of the optical reference lines for 8 MMW sub-carriers DWDM transmission incorporating OSSB or ROSH. All listed frequencies are relative to 193.8 THz. “no inter”: wavelengths are not interleaved, “inter”: wavelengths are interleaved. (Unit: GHz)

<table>
<thead>
<tr>
<th>No.</th>
<th>USC, no inter</th>
<th>ESC, no inter</th>
<th>USC, inter</th>
<th>ESC, inter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-284.5</td>
<td>-350</td>
<td>-164.5</td>
<td>-140</td>
</tr>
<tr>
<td>2</td>
<td>-204.5</td>
<td>-250</td>
<td>-144.5</td>
<td>-100</td>
</tr>
<tr>
<td>3</td>
<td>-123.5</td>
<td>-150</td>
<td>-63.5</td>
<td>-60</td>
</tr>
<tr>
<td>4</td>
<td>-41.5</td>
<td>-50</td>
<td>-41.5</td>
<td>-20</td>
</tr>
<tr>
<td>5</td>
<td>+41.5</td>
<td>+50</td>
<td>+41.5</td>
<td>+20</td>
</tr>
<tr>
<td>6</td>
<td>+125.5</td>
<td>+150</td>
<td>+65.5</td>
<td>+60</td>
</tr>
<tr>
<td>7</td>
<td>+210.5</td>
<td>+250</td>
<td>+150.5</td>
<td>+100</td>
</tr>
<tr>
<td>8</td>
<td>+296.5</td>
<td>+350</td>
<td>+176.5</td>
<td>+140</td>
</tr>
</tbody>
</table>

MMW sub-carriers DWDM transmission incorporating OSSB or ROSH, the frequency slots number can be obtained and are listed in Table 2, for both cases with and without wavelength interleaving. Generally, a minimum optical frequency $f_i$ should be designated first then other frequencies can be obtained by $f_i = f_i + S_i \Delta f$. Here, as a worst-case is assumed, we take the zero-dispersion point of the ZDSF as the middle of the DWDM frequency range (thus the FWM efficiency can be the highest [11]). 193.8 THz (1548 nm) as the middle frequency is assumed, and then the optical frequencies of the reference lines can be obtained and the number relative to 193.8 THz are listed in Table 3. In order to make comparison to conventional DWDM transmission employing equally spaced channels (ESC), ESC DWDM transmission is also simulated. In the case without wavelength interleaving, in ESC DWDM transmission the frequency difference between the reference lines is assumed to be an ITU-standard 100 GHz. While when wavelength interleaving is assumed, the frequency difference is assumed to be 40 GHz, by which the reference lines and the information lines can be equally interleaved [18]. In ESC systems the middle frequency is also assumed to be 193.8 THz, which is the assumed zero-dispersion point of the ZDSF. The corresponding relative frequencies to 193.8 THz are also listed in Table 3.

We mainly investigate the link performance of the 4-th MMW sub-carrier transmission, which is the one affected most by FWM crosstalk as the corresponding reference line and the information line are the closest to the zero-dispersion point of the ZDSF [11]. In the simulation, all of the 8 originally multiplexed optical wavelengths are modulated in format of OSSB, and the 4-th one carries 622 Mbit/s BPSK data via 60 GHz sub-carrier. The simulated BER as function of optical channel power is shown in Fig. 4. Clearly can be seen in Fig. 4, along the increase of the optical channel power, the BER of the ESC case without wavelength interleaving decreases first due to faster increase in signal-to-noise ratio (SNR) than FWM crosstalk effect. However, as FWM power

Fig. 4. Simulated BER as function of channel power, for 622 Mbit/s BPSK data transmission on 60 GHz sub-carrier over 40 km of ZDSF, with 8 wavelengths multiplexed.
is proportional to cube of the input optical channel power $P_c$ [11], while the SNR is only roughly proportional to $P_c$, the BER increases after 3 dBm, as the FWM crosstalk effect increase faster than SNR. When the optical channels are unequally spaced using the frequency allocation as listed Table 3, in case wavelength are not interleaved, even after 3 dBm, the BER decreases very fast, since most of the FWM crosstalk are excluded from the signal channels. In the cases wavelengths are interleaved, comparison between the BER performances between cases of ESC and USC also indicates that when USC is applied the FWM crosstalk can be minimized by using the present method.

IV. CONCLUSIONS

Method minimizing FWM crosstalk by unequally spacing channels in MMW DWDM transmission over ZDSF with equal MMW sub-carrier frequencies is presented in this paper. We showed that except the ones bound to be generated at the signal channels, all other FWM products can be excluded from the signal channels by using the proposed method. Simulation using commercial software verified the proposed method.

REFERENCES


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