Using Tunable Dispersion-Compensated Modules to Overcome the Power Penalty of a Millimeter-Wave Opto-Electronic Oscillator Signal that is Distributed via a Passive Optical Network for 5G Networks

Mehmet Alp Ilgaz, Bostjan Batagelj
University of Ljubljana, Faculty of Electrical Engineering,
Ljubljana, Slovenia
mehmet.ilgaz@fe.uni-lj.si

Abstract—The opto-electronic oscillator (OEO), used as a high-frequency oscillator to produce millimeter-wave (mm-W) signals with a low phase noise, is a suitable candidate for fifth-generation (5G) networks in the mm-W range. Since a mm-W OEO is too expensive for every 5G base-station, another option is to employ the OEO at the central-office to feed the base-stations via a passive optical network (PON) infrastructure. The lengths of the PON branches introduce a large power penalty to the transmitted mm-W OEO signal due to the chromatic dispersion of the optical fiber. In this paper the idea of upgrading the PON branches with tunable dispersion-compensated modules to have power-penalty-free transmission is proposed. By overcoming the power-penalty problem in the mm-W range, the integrated optical dispersion-compensated modules are used to minimize the influence of the dispersion in the standard single-mode optical fiber used in the PON.

Keywords—5G mobile networks, tunable dispersion-compensated module, power penalty, chromatic dispersion

I. INTRODUCTION

Fifth-generation (5G) mobile networks will be more effective than the previous generations, such as 3G and 4G (LTE). The low latency and high bandwidth will increase the efficiency for the user. In order to meet these requirements, the data bit rate should be increased as well. Unlike previous technologies, in 5G mobile networks, millimeter-wave (mm-W) signals (30–300 GHz) will be used [1].

Usually, the mm-W frequencies are generated by the frequency multiplication of a high-quality micro-wave oscillator signal. In the case of such harmonic frequency multiplication, additional signal processing, e.g., filtering, is required and the phase noise increases at each stage of the multiplication. Therefore, we prefer to generate mm-W frequencies directly using an opto-electronic oscillator (OEO). When using this approach, high-bandwidth components are required in the mm-W oscillator. However, the electrical amplifier, the filter and the modulator represent an important limitation on the generated frequencies, but the most important parameter for a high-bandwidth 5G network is the low-phase-noise signal that comes from the OEO. Since an OEO is too expensive to have one at every base-station, we are proposing to have only one such high-quality source in the central-office and then distribute its signal over the radio access network to many base-stations. However, one of the well-known problems in this high-frequency range is the power penalty of the transmitted signal via the fiber-optic link due to chromatic dispersion [2].

In this paper we show a new idea that can be used to avoid the chromatic dispersion effect in the case when the signal from the OEO is transmitted over a dark-fiber passive optical network (PON). This new idea is based on tunable dispersion-compensated modules (TDCMs) that can be used at all the base-stations of a 5G mobile network to avoid the chromatic dispersion. The advantage of this system is that it compensates the chromatic dispersion for the whole length of the fiber branch and can be tuned for all frequencies.

This paper is organized as follows. In the next section we will introduce the OEO for the mm-W range. Then the system approach is described by introducing the idea of distributing the mm-W signal from the central-office to the base-stations over a PON and the use of a TDCM at the end of each PON branch. This is followed by a simulation on a single fiber-optic link to show the quality of the system. At the end of the paper the conclusions are drawn.

II. MILLIMETER-WAVE OEO

An opto-electronic oscillator (OEO) consists of the optical and electrical components necessary to produce mm-W signals [3-6]. In the optical part there is an analog optical fiber link that is composed of a laser, an opto-electronic modulator, an optical fiber and a photodiode. In general, above 10 GHz, external modulation (with an external opto-electronic modulator) is used. The working principle of the OEO can be described as the optical signal is produced by a continuous wave (CW) laser and modulated by an opto-electronic modulator. The modulated optical signal is transferred by a low-loss optical fiber to the photodetector. The photodetector converts the optical signal to an electrical signal. The loss of the electrical signal is then compensated by an electrical amplifier. An electrical bandpass filter is used to determine at which frequency the OEO oscillates and filters the other modes. The simple configuration for a single-loop OEO in a mm-W signal application is shown in Fig.1.

Fig. 1. Single-loop OEO configuration.

The literature describes many different configurations of the single-loop OEO. Some configurations use optical components. The semiconductor optical amplifier (SOA) or Erbium-Doped Fiber Amplifier (EDFA) [7] can be used as an optical amplifier. Optical filters such as the finesse etalon [8], photonic filter [9], or hybrid band-pass filter [10] can be implemented. But, in general, optical solutions are more expensive than electronic solutions.

One of the reasons for implementing an OEO for 5G mobile networks is to make the system as cheap as possible. Therefore, our aim is to employ an electrical amplifier and an electrical filter for this application. They are cheaper solutions than the optical

one and can be easily built up. In addition, they are widely available on the market. One of the biggest disadvantages of using an electrical amplifier is that it contributes to the phase noise of the OEO [11-12]. One of the main advantages of the OEO is that it has a high Q (Quality) factor that is proportional to the length of the optical delay line. Another advantage is that the phase noise of the OEO is not increasing with the frequency, thanks to the resonator's properties.

III. DISTRIBUTION OF THE MILLIMETER-WAVE OVER THE PON

The PON infrastructure is used to transmit data from the central-office to the end users in optical access networks. They are only composed of passive optical components (combiners/splitters/couplers). The PON has a passive optical splitter to distribute the optical signal to many (in some cases up to 128) end users. The typical PON architecture is shown in Fig.2. The length between the end user and the central-office can vary from a few kilometers up to 20 km, and it depends on the actual geographical location.

Fig. 2. Basic configuration of a PON.

One of the ideas described in [13] is to use the dark fiber of an already-existing PON infrastructure for the distribution of the OEO signal. This has the advantage of decreasing the total cost of the base-stations of the 5G mobile networks. The OEO produces a high, stable, mm-W signal and this signal can be distributed via a PON to the many base-stations. The idea is shown in Fig.3.

Fig. 3. One possible idea to deliver the OEO signal to base-stations via a PON. A high, stable signal will be delivered to the base-stations [13].

With this idea shown in Fig.3 we can simplify the base-stations of 5G mobile networks [13]. This system is based on a radio-over-fiber system (RoF) [14]. One of

the possible problems of this configuration was mentioned in [15-18]. It explains the power-penalty problem due to the chromatic dispersion. The 1550-nm wavelength is very popular in optical signal generation because of the low optical losses (0.2 dB/km) [19]. This power-penalty problem is clearly seen in the mm-W signal with a 1550-nm wavelength. This is also a major problem for the idea described in [13], because the optical signal generated by the OEO is transferred by the PON, which is already positioned and composed of a single-mode fiber that is affected by chromatic dispersion. A single-mode optical fiber G.652D or G.657A with a dispersion coefficient of approximately 17 ps/(nm·km) at the 1550-nm wavelength is used for the PON infrastructure. Since the maximum length of the PON is 20 km, the maximum accumulated dispersion is 340 ps/nm.

The literature has some suggestions for decreasing or removing the chromatic dispersion effect in a standard single-mode fiber. One well-known method is to employ a 1310-nm wavelength laser instead of the 1550-nm version. There is another method involving a dual-drive Mach-Zehnder Modulator (MZM) to produce a Signal Side Band (SSB) signal [20]. There are other methods that use a specific fiber such as a Dispersion-Shifted Fiber (DSF) to avoid the chromatic dispersion. These systems have some disadvantages for 5G mobile networks. For instance, to use a 1310-nm wavelength the laser has a higher optical loss compared to a 1550-nm wavelength laser. On the other hand, it is very expensive to change the PON with the Dispersion Compensated Fiber (DCF) or DSF to avoid the power penalty. Moreover, to use a dual-drive MZM to produce the SSB signal is not useful for 5G mobile networks.

IV. USE OF TUNABLE DISPERSION-COMPENSATED MODULES IN A PON

There are some different configurations for dispersion management when using TDCM. One possible configuration is to use chirped fiber Bragg gratings [21-23]. With this configuration, the change in the temperature of the module can be used to tune the module. Another solution for dispersion management is to use some specific fibers, such as a dispersion-shifted fiber [21], [24]. There is also another method that uses arrayed waveguide grating for dispersion-compensated modules [25]. There is also another management solution to use the chirp control of a semiconductor optical amplifier (SOA) [26].

For instance, the market offers fixed dispersion-compensated modules that cover the dispersion accumulated over 40 km of standard single-mode fiber. The advantage of using a TDCM is to fix the chromatic dispersion of the fiber having an exact length. With this approach each base-station has a TDCM, so all the distributed signals are protected from the power-penalty problem. The reason for that is the different optical fiber lengths between each base-station and the central-office, where the OEO is located. The new idea is shown in Fig. 4.

Fig. 4. A possible combination of the idea described in [13] with TDCM is to avoid chromatic dispersion.

This idea is shown in Fig. 4, the TDCM is inserted at the end of each PON branch in the base-station and is located in front of each photodiode. Due to the different lengths of the PON branches, each TDCM is tuned to a value so as to compensate for the accumulated dispersion. Since each TDCM inserts an additional few decibels of loss, the number of branches (or base-stations) must be reduced. This disadvantage can be avoided by placing an optical amplifier (SOA or EDFA) in the PON trunk [19]. Unfortunately, these additional optical amplifiers can contribute to the phase noise of the oscillator signal [27]. The advantage of this system is the tunability of the base-station. In other words, inserting the TDCM in each base station of a 5G network gives an advantage to the designer of the OEO, thanks to its tunability. With this tunability opportunity, it is possible to change the optical length of the OEO or the electrical bandpass filter of the OEO, if required. The simulated TDCM works between the 1527.994 nm and 1566.314 nm wavelengths, where we decide to use the OEO in the 1550-nm wavelength.

V. SYSTEM SIMULATIONS

In this part we will make simulations to prove that it is possible to compensate for the chromatic dispersion of the different lengths of the PON for the same operating frequency. We will start our simulations in the micro-wave region and then in the mm-W region to show how the chromatic dispersion becomes more dominant in the mm-W region than in the micro-wave region. The simulations will be made via the 1550-nm wavelength region. This is a very popular region for the OEO because of the lower optical loss characteristics than for the other regions. Firstly, we will demonstrate the chromatic dispersion behavior in the micro-wave and mm-W ranges. The simulation in Fig.5 shows the result for the 10- and 39-GHz single-loop OEO with an optical length of 0 km to 50 km.

Fig. 5. Chromatic dispersion effect on the 10-GHz (red) and 39-GHz (blue) OEO signals with a 1550-nm wavelength laser.

It is clear from the simulation results in Fig.5 that the chromatic dispersion is dominant in the mm-W region. In the next step we will place the TDCM as defined in Fig.4 to compensate for the dispersion penalty on the OEO's signal with a specific optical length thanks to the tunability of the TDCM. In order to test the idea, we will conduct different simulations. The simulation uses a TDCM based on fiber Bragg gratings. First, we will tune the TDCM to a 14.4-km optical fiber length where the PON has 10 km and the length of the single-loop OEO is 15 km. The operating

frequency of the measurement is selected to be 16 GHz, where the dispersion should be lower compared to the mm-W range. Fig.6 shows the simulation for the power penalty occurring with the TDCM.

Fig. 6. Chromatic dispersion where the TDCM is tuned to the 14.4-km optical fiber length and the operating frequency is 16 GHz. The red line shows the power penalty for the OEO with TDCM and the blue line shows the power penalty for the OEO without TDCM.

It is clear that the power penalty does not occur for the exact length where the TDCM is tuned at 14.4 km (where the TDCM will set to approximately -245 ps/nm to compensate for the dispersion). But, on the other hand, the power penalty occurs in the same optical length if the TDCM is not combined with the SMF.

In the next simulations we will move to the mm-W range signal. The frequency is selected as 39 GHz and we increase the optical fiber length from 0 to 50 km to show the chromatic dispersion effect. The TDCM is tuned to 36.1 km in the base-station to avoid the chromatic dispersion. At the same time we will make the simulation without the TDCM to show the effect on the TDCM at 36.1 km. The simulations are shown in Fig.7.

Fig. 7. Chromatic dispersion where the TDCM is tuned to the 36.1-km optical fiber length where the operating frequency is 39 GHz. In this case the TDCM is set to approximately -614 ps/nm. The red line shows the power penalty for the OEO with TDCM and the blue line shows the power penalty for the OEO without TDCM.

According to the results from Fig 5 to Fig. 7, the first thing we see is that the dispersion is more dominant in the mm-W range than in the micro-wave region below 20 GHz. In addition, for the tuned optical length of 36.1 km the system is protected from chromatic dispersion thanks to the TDCM, as shown in Fig. 7. In the next step we fix the optical fiber length at 40 km and tune the dispersion-compensating module

to a 40-km length compensation. We then change the operating frequency from 10 MHz to 40 GHz to see whether there is any power penalty due to the chromatic dispersion.

Fig. 8. Chromatic dispersion where the TDCM is tuned to 40 km of the optical fiber length, where the operating frequency is from 10 MHz to 40 GHz. In this case the TDCM is set to approximately -680 ps/nm.

From the results in Fig.8 we see that no power penalty occurred in the link from the OEO to the base-station via the PON if there is correct tuning on the TDCM. One of the disadvantages of this idea is the large increase of the insertion loss (IL) compared to the use of an SMF (fiber-Bragg-grating-based TDCM has an IL of approximately 6 dB where the SMF has an IL of 0.2 dB/km).

The simulation results shown in Fig.5 to Fig.8 give a hint about a new idea for implementing the OEO with TDCM in a 5G mobile network. The mm-W range is very demanding and a complete mm-W signal distribution system together with the single-loop OEO should be carefully designed. The connectors, the CW laser, the external modulator (Mach-Zehnder modulator [28] or the electro-absorption modulator [29]), the electrical filter and the amplifier should be carefully designed to operate efficiently in the mm-W range. As explained and shown in this paper for the design of an OEO in the mm-W range, one of the critical parameters is the power penalty due to the chromatic dispersion. Chromatic dispersion not only causes a phase shift, but also cancels the signal via transmission [15].

The system simulation is designed on a simple network based on a point-to-point link. But one of our ideas in [18] is to use this idea in a more complex network where several different lengths exist. This means we will feed more than one base-station from the central-office with a single oscillator link. In this case in each base-station the TDCM should be tuned with regards to the total optical length of the OEO and the PON. Since using an optical time reflectometry measurement for the optical length determination is introducing additional noise, we are proposing two feedback loops (Fig. 9). This automatic tuning design system will be implemented in each base-station with a TDCM that receives the oscillator signal from the central-office.

Fig. 9. Automatic feedback-loop tunability of the TDCM. Option 1 is based on an electrical signal, while option 2 is based on an optical signal.

With Fig. 9 there are two options to tune the TDCM automatically. In the first feedback loop the mm-W signal is converted to an electrical signal and then fed back to the TDCM. In the power meter (P) electrical power is measured and the dispersion is tuned to achieve the maximum value of the electrical power. If it does not catch it by lowering the dispersion coefficient then it goes the other way to increase the dispersion coefficient to catch the maximum power. When the maximum electrical power is obtained the dispersion effect is minimized. The second option has the same idea, but in this case the optical signal is used. Here, no electrical-to-optical signal conversion is required to obtain the information about the signal distortion. The signal in the optical domain is used to measure the power (P) and further feedback to the TDCM. If we use an electrical feedback loop an additional signal processing of the mm-W signal is needed. For this reason we are planning to implement an optical feedback.

VI. CONCLUSION

In this paper we discuss the idea of avoiding chromatic dispersion in an OEO by delivering the optical signal via a PON. This idea is not a cheap solution to avoid chromatic dispersion, but it is a very useful solution if the network operators would like to implement an OEO in the 1550-nm range. The operating frequency for 5G mobile networks is still an open issue, but it is almost sure that it will be located in the mm-W region. With this idea, when the OEO is inserted into the central-office, first, the number of base-stations that should be fed by this central-office needs to be determined. The next step is that the PON length should be measured for each base-station. And the final step is that the TDCM should be tuned to the exact length of the PON and the optical length of the OEO. After that, there are some final tunings required, such as measuring the optical signal that is received by each base-station. Based on this, the SOA or EDFA can be located. After that it will be very useful to measure the phase noise of the OEO in the central-office and the one received by each base-station, and then make a comparison of the signals between the central-office and the base-station.

We believe that integrated optics and especially integrated micro-wave photonics can lower the price of the TDCMs integrated with photoreceivers and a mm-W base-station frontend and can bring this solution close to the market.

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