

Dispersion Limitation of Digital Signal and Carrier Distribution in Optical-Wireless Networks

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Abstract — Modern communication systems, such as mobile 5G and future 6G require ultrawide bandwidths and low latencies in the anyhaul (i.e., front- and backhaul) networks interconnecting the data center and cloud-core with the subscribers through cell sites. Extremely high data rates and low latencies are expected in several applications. When integrating the building blocks into complete networks, a strict limitation is raised by the optical fiber. Dispersion effects significantly reduce the bitrate-distance product between the optical nodes. In the paper the effect of chromatic dispersion limitation is investigated both for baseband digital data and for microwave and millimeter-wave radio-frequency signals (RF), e.g. RF carriers. Experimental verification shows the limited bandwidth of the singlemode optical fiber as a function of fiber span and modulating frequency. In feasible systems the focus is on flexible and future-proof architectures. Future 6G and actual 4G/5G hybrid wireless-optical networks have simultaneous economic and technical goals to provide increased throughputs. Due to the high density of the cell sites it is crucial to reduce energy consumption, size and costs of radios and remote antenna heads. Some system design rules of thumb are listed in the paper, and finally the RF carrier generation methods are reviewed in the paper.

Keywords — 6G, 5G, 4G, anyhaul, optical fiber, microwaves, millimeter-waves, chromatic dispersion, RF carrier, FSO.

I. INTRODUCTION

The various domains of wired and wireless optical and radio transmission of digital baseband (BB) and radio-frequency (RF) signals are widely discussed in the literature [1]-[9]. Wideband electrical and optical components with exceptional bandwidths – even beyond 100 GHz – are commercially available since several years [1]-[12]. Many scientific papers focus on leading, top and world record results. Such results are often achieved using optimized or special environments, under experimental conditions, demonstrated in laboratory, e.g. using novel modulation modes or tested only for reduced distances [10],[13] or with limited number of users [14]. However, actual 5G and future beyond 5G (B5G) or 6G systems require industry level reliable and flexible solutions, that are running in real-life conditions and even under extremely high traffic loads. In our paper first we describe the effect of chromatic dispersion when BB and RF signals are transmitted optically over standard singlemode fiber (SSMF). The approach is generic, we focus on feasible system design [15]-[18]. Finally, the various system proposals are overviewed that support the goal of achieving smaller, simpler, and cost-effective solutions for mmW carrier generation [19]-[23].

II. NETWORK REQUIREMENTS AND EXPECTATIONS

For feasible business cases, reasonable cost-benefit and predictable return of investments (RoI) are required [24]. Such

approach mandates network components having simplified architecture, affordable price and realistic size without risking the goals of RoI, flexibility and operability. At the same time, all network components are expected to support remote control, configuration and management jointly with data collection possibility for performance monitoring and network statistics [14]. Even though dispersion shifted fibers are available, it is not reasonable to replace existing fibers in running networks that provide service for thousands of subscribers. The typical network (NW) topology is shown in Fig. 1, where the optical anyhaul is extended by wireless transmission, e.g. by mobile and fixed microwave (μ W), by fixed millimetric-wave (mmW) radio links and free space optics (FSO). The focus is on commercially available components, and we evaluate the reviewed methods from system applicability point of view.

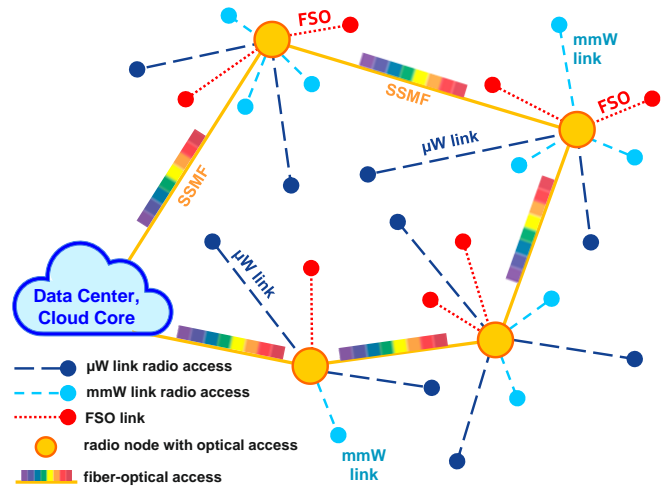


Fig. 1. 4G/5G/B5G/6G hybrid wireless-optical network.

Increasing density of 5G/4G and forthcoming 6G radio cell sites mandate smaller size, lower cost and energy-efficient radio transceivers and antenna heads [25]. Fixed wireless (μ W and mmW) radio hops and FSO links connect remote antenna heads, which do not have (yet) direct fiber-optical access. Fig. 1 shows the high-capacity fiber-optical ring (e.g. DWDM and GbE: dense wavelength division multiplexing with Gigabit Ethernet) connected to wireless nodes. The general system requirements expected from the network elements are high throughput, i.e. Gigabit/second (Gbps) bit rates, small size, low power consumption, possibility of beamforming with high antenna gains to access both fixed and mobile subscribers [1]-[4]. Frequent network expansions and optimization mandate remote control for the baseband, RF and optical units, including several parameters, such as selectable channels, RF carriers, modulation mode, bandwidth, data rate, etc. [25]-[28].

As it is discussed in parts III and IV of the paper, chromatic dispersion of the SSMF significantly limits the transmission performance both for BB digital and for analog RF carriers or modulated RF signals. In digital systems, dispersion results in broadening of the transmitted pulses. Overlapping symbols cause inter symbol interference (ISI), and finally degradation of the link bit error rate (BER). The effect of chromatic dispersion in time domain is visible as broadening of the pulses that compose the baseband digital signal. In digital transmission, dispersion of the optical fiber limits the maximum number of information bits (or symbols), which can be transmitted within a time period through the fiber without overlapping. Dispersion broadens all the consecutive pulses, forming each received symbol overlapping several adjacent symbol intervals. In the microwave frequency domain, the transfer function of the dispersive optical fiber is a lowpass filter with multiple ‘bandpass filter-like’ ranges in addition.

III. EFFECT OF DISPERSION ON DIGITAL SIGNALS

Around the optical carrier ω_0 the propagation constant $\beta(\omega)$ can be approximated by a Taylor-series (up to the second order) [4],[29],[30]:

$$\begin{aligned} \beta(\omega) &\approx \beta(\omega_0) + \beta'_0(\omega - \omega_0) + \beta''_0 \frac{(\omega - \omega_0)^2}{2} = \\ &= \beta_0 + \beta'_0 \Delta\omega + \beta''_0 \frac{\Delta\omega^2}{2}. \end{aligned} \quad (1)$$

Having an optical spectral bandwidth $\Delta\omega = \omega_{\max} - \omega_{\min}$ of the signal to be transmitted, the propagation time difference ΔT at the end of the L km long optical fiber is [4]:

$$\Delta T = \frac{dt_g}{d\omega} \Delta\omega = L \frac{d}{d\omega} \left(\frac{1}{v_g} \right) \Delta\omega = L \frac{d^2\beta}{d\omega^2} \Delta\omega, \quad (2)$$

where $t_g = L/v_g$ is the group delay, and $v_g \triangleq d\omega/d\beta$ represents the group velocity. Substituting $\Delta\omega = -2\pi c \Delta\lambda / \lambda_{\text{opt}}^2$ into equation (2):

$$\Delta T = L \frac{d}{d\lambda} \left(\frac{1}{v_g} \right) \Delta\lambda = - \frac{2\pi c}{\lambda_{\text{opt}}^2} \frac{d^2\beta}{d\omega^2} L \Delta\lambda = |D| L \Delta\lambda. \quad (3)$$

As seen in equation (3) the time difference ΔT is proportional to the fiber length L and the spectral width $\Delta\lambda$ of the modulated optical signal. The constant of proportionality D [ps/(km·nm)] is called the dispersion parameter [4],[30],[31]:

$$D = \frac{1}{L} \frac{dt_g}{d\lambda} = - \frac{\omega^2}{2\pi c} \frac{d^2\beta}{d\omega^2} = - \frac{2\pi c}{\lambda^2} \frac{d^2\beta}{d\omega^2} = - \frac{2\pi c}{\lambda^2} \beta''_0. \quad (4)$$

Several papers discuss chromatic dispersion as a function of wavelength [29],[31]. Around $\lambda_{\text{opt}} = 1310$ nm the Standard Singlemode Fiber (SSMF) has nearly zero dispersion. Unfortunately, at $\lambda_{\text{opt}} = 1550$ nm, the typical dispersion parameter of SSMF is around $D \approx 17$ ps/km/nm [2],[4],[29]-[32]. Broadband 4G/5G/6G anyhaul networks employ multiple optical channels operating at different wavelengths [2],[6],[7],[9],[10]. It is emphasized, that in such transport networks, e.g. in DWDM systems, capacity expansions are required continuously. Due to regular expansions, optimizing high-speed baseband transmission for specific low-dispersion wavelengths would not result in a future-proof solution for flexible systems. There are low dispersion wavelengths at some channels, where D is small enabling higher bitrates. But as more and more optical channels are involved, some other channels would suffer higher dispersion, since the demand is continuous for increased throughputs. On the other hand, in urban and in dense urban environments, the optical-fiber lengths can be kept relatively short. Maximum L is typically a few tens of kilometers between the connected optical nodes, e.g. GbE routers or add-drop multiplexers (ADM) [7],[16]-[18],[32].

The analog bandwidth B required by a digital baseband signal is depending on the modulation mode, bit rate R and the exact pulse shape of the line code, e.g. return-to-zero (RZ), or non-return-to-zero (NRZ) code. Advanced optical modulations employ symbols instead of bits, e.g. n -PAM, pulse-amplitude-modulation, or optical QAM [33]-[36] but reduce hop length and increase the complexity. Assuming NRZ code, a -3 dB (electrical dB) bandwidth of $B \approx 0.75 \cdot R$ can be considered, see for example Agilent application note for SDH filters [37]:

$$B \text{ [Hz]} \cong 0.75 \cdot R \text{ [bit/s]} = 0.75/T_{\text{bit}}. \quad (5)$$

Approximation of B with 75% of the bit-rate R in equation (5) is a general ‘rule of thumb’ without any specific optical link or Signal-to-Noise Ratio (SNR) requirement. IEEE GbE task force defines standardized filters for reference receivers. For 25 Gbps receivers, the -3 dB filter is defined as $B = 0.75 \cdot 25 = 18.75$ GHz [17]. As another example, let us consider a BB digital NRZ signal of $R = 2.5$ Gbps (\sim transport mode STM-16 in synchronous digital hierarchy, SDH). The spectral width in electrical domain is approximated as $B = 0.75 \cdot 2.5 = 1.875$ GHz [37]. The pulse duration $T_{\text{bit}} = 1/R = 1/(2.5 \text{ Gbps}) = 400$ ps. The pulse broadening ΔT –in time domain– can be estimated using equations (3)-(7):

$$\begin{aligned} B &= \frac{c}{\lambda_{\text{opt}}} - \frac{c}{\lambda_{\text{opt}} + \Delta\lambda} = \frac{c(\lambda_{\text{opt}} + \Delta\lambda) - c\lambda_{\text{opt}}}{\lambda_{\text{opt}}(\lambda_{\text{opt}} + \Delta\lambda)} = \\ &= \frac{c\Delta\lambda}{\lambda_{\text{opt}}(\lambda_{\text{opt}} + \Delta\lambda)} \approx \frac{c\Delta\lambda}{\lambda_{\text{opt}}^2} \rightarrow \\ \Delta\lambda &\approx \frac{B}{c} \lambda_{\text{opt}}^2 = \frac{0.75R}{c} \lambda_{\text{opt}}^2, \end{aligned} \quad (6)$$

where c is the speed of light. The relative pulse broadening of $\Delta T/T_{\text{bit}}$ (calculated with $D \approx 17$ ps/km/nm fiber dispersion) is:

$$\frac{\Delta T}{T_{\text{bit}}} [\%] = \frac{DL\Delta\lambda}{1/R} \cdot 100\% = \frac{75DL}{c} R^2 \lambda_{\text{opt}}^2. \quad (8)$$

For the 2.5 Gbps STM-16 signal, equation (8) gives less than 4% relative pulse broadening for fiber spans up to 60 km. For 10 Gbps data rate however, the pulse broadening can reach 40% at 40 km. Thus a significant pulse overlap –and such an eye closure– is expected [34]. This leads to BER degradation in the digital link. Table I summarizes calculated and measured electrical bandwidths (BW) of $L = 10, 20, 30, 40, 50$ and 60 km standard singlemode fibers, around the optical carrier $\lambda_{\text{opt}} = 1550$ nm. Using the electrical BW – bit rate relation of equation (5), estimated NRZ throughputs can be calculated. Please note, that lower fiber dispersion values, special pulse shaping methods (i.e. roll-off factor [33]), optimized transceiver structures, or changing NRZ to 4-PAM can result better digital throughputs compared to the values indicated in Table I [34].

TABLE I. BASEBAND THROUGHPUT ESTIMATION ($\lambda_{\text{opt}} = 1550$ nm)

fiber length L [km]	calculated -3 dB BW [GHz]	measured -3 dB BW [GHz]	calculated NRZ throughput [Gbps]
10	13.536	Fig.5	18.05
20	9.572	Fig.6	12.76
30	7.815	Fig.7	10.42
40	6.768	Fig.8	9.02
50	6.054	Fig.9	8.07
60	5.526	Fig.10	7.37

The maximum fiber length $L_{3\text{dB}}$ with 3 dB electrical passband for modulation frequencies f_{RF} can be calculated as [4],[30]:

$$L_{3\text{dB}}(D, f_{\text{RF}}, \lambda_{\text{opt}}) = \frac{c \cdot \arccos(10^{-0.15})}{\pi D f_{\text{RF}}^2 \lambda_{\text{opt}}^2} \approx \frac{c}{4D f_{\text{RF}}^2 \lambda_{\text{opt}}^2}. \quad (9)$$

The RF and opt indices differentiate between radio (GHz) and optical (THz) signals. Rearranging eq. (9) for f_{RF} at 3 dB BW:

$$f_{RF}(D, L, \lambda_{opt}) \approx \frac{1}{2\lambda_{opt}} \sqrt{\frac{c}{DL_{3dB}}} \quad (10)$$

Fig. 2 plots the relation of -3 dB electrical bandwidth and expected NRZ bit rates as a function of fiber length L . (Dispersion parameter $D=17$ ps/km/nm has been used in the calculations.)

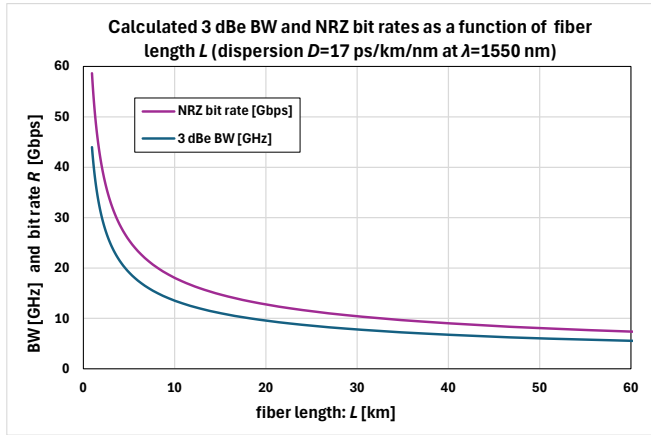


Fig. 2. 3 dB bandwidth values and expected NRZ bit rates, calculated as a function of dispersive fiber length L .

IV. EFFECT OF DISPERSION ON RADIO FREQUENCY SIGNALS

Considering optical Intensity Modulation / Direct Detection (IM/DD) transmission over dispersive fiber links, the detected optical power suffers significant penalty from chromatic dispersion (Fig.3-10.) [4],[9],[19],[20],[23],[32]. At specific f_{RF} modulation frequencies, the RF signal is completely rejected, as it is seen in equations (11)-(12) [4],[30] and in Figures 3-4. The rejected μ W frequencies are also clearly visible in our laboratory experiments: the measured fiber transfer functions are plotted in Fig. 5-10. For comparison, the calculated 3 dB bandwidth frequencies are marked in the measured fiber transfer function plots with blue dashed lines (Fig. 5-10). Please note, that the entire optical link is treated as a microwave two-port. The transmitter and receiver side electrical-to-optical (E/O) and optical-to-electrical (O/E) conversions are included in the calibrated measurements [38]-[42].

$$P_{RF}[\text{dB}] \propto 20 \log_{10} \left| \cos \left(cD\pi L \left(\frac{f_{RF}}{f_{opt}} \right)^2 \right) \right| = \quad (11)$$

$$= 20 \log_{10} \left| \cos \left(\frac{D\pi L}{c} (f_{RF} \lambda_{opt})^2 \right) \right|$$

$$f_{RF, rej, k}(L, D) = \frac{1}{\lambda_0} \sqrt{\frac{c(2k+1)}{2DL}}, \quad k \in N. \quad (12)$$

Table II lists the calculated and measured first and second microwave rejection frequencies ($f_{RF, rej, 1}$, $f_{RF, rej, 2}$) for different optical fiber lengths ($L=10$ to 60 km in 10 km steps).

TABLE II. REJECTION FREQUENCIES OF IM/DD OPTICAL TRANSMISSION				
tested fiber length L [km]	calculated 1 st rejection [GHz]	measured 1 st rejection [GHz]	calculated 2 nd rejection [GHz]	measured 2 nd rejection [GHz]
10	19.158	18.522	33.182	>> 20
20	13.546	13.217	23.463	>> 20
30	11.061	10.833	19.158	19.3
40	9.579	9.301	16.591	16.5
50	8.568	8.353	14.839	14.9
60	7.821	7.677	13.546	13.482

As seen, due to the unwanted effect of chromatic dispersion, the bandwidth of standard single-mode optical fiber cannot be considered as nearly 'infinite'. At any fixed f_{RF}

modulation frequency, the optically transmitted IM/DD signal may suffer complete rejections, periodically as a function of fiber length L . In the frequency domain, these rejections are visible more and more often with the increase of the f_{RF} modulation frequency.

As a conclusion, the SSMF bandwidth is significantly limited when optical carriers are used around $\lambda_{opt} = 1550$ nm. As seen in equation (11) the fiber penalty function is periodic as a function of fiber length. Fig. 3 plots calculated penalty for millimetric-wave carriers of 42 GHz, 58 GHz and 80 GHz, which are typical frequencies already used in the anyhaul of 5G/4G systems and also good candidates for future B5G/6G anyhaul networks. In frequency domain, the rejected frequencies are more and more frequent.

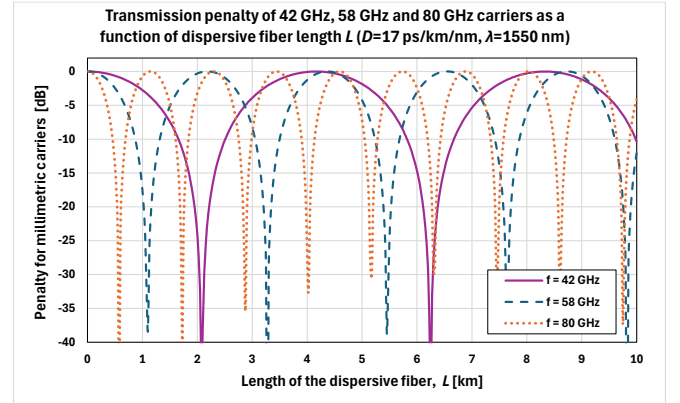


Fig. 3. Calculated transmission penalties for $f_{RF} = 42$ GHz, 58 GHz and 80 GHz millimetric-wave carriers delivered over SSMF.

Fig. 4 plots the rejected microwave and mmW frequencies as a function of fiber length. In flexible anyhaul networks, due to topology changes or dynamic re-routing, L may change over time [18],[43]. Fig. 4 indicates the difficulty of the optical transmission of such high frequency carriers when fiber dispersion cannot be neglected. In realistic environments and in network planning practice it is very difficult to transfer mmW carrier frequencies over long fibers that have dispersion. When special dispersion compensation techniques or specified fiber lengths are used, the flexibility in a dynamically changing dense network mesh is lost. In real-life 4G/5G and future 6G networks, new and newer cell sites must be frequently integrated. On the other hand, old site locations often become obsolete and must be demolished. In dense urban environments having high new buildings, chimneys, (temporary) cranes or growing trees the radio signals may be blocked. As the built environment changes continuously, the 4G/5G/6G networks must be able to react for these changes quickly. Fixing hop lengths or well selected frequencies to constant values is not a viable option in flexible and commercial networks.

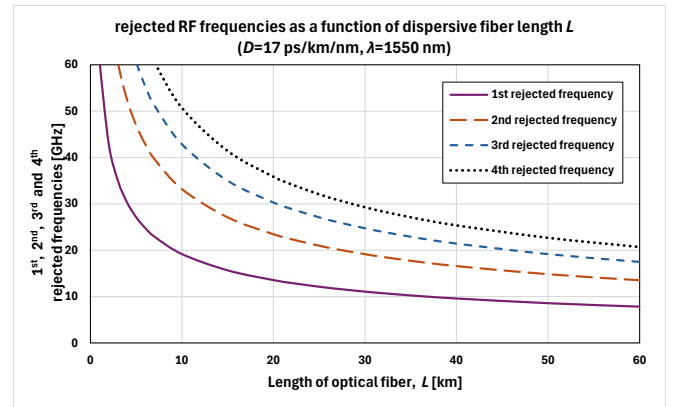


Fig. 4. Calculated frequencies where the optically transmitted IM/DD radio-frequency signal f_{RF} is completely rejected.

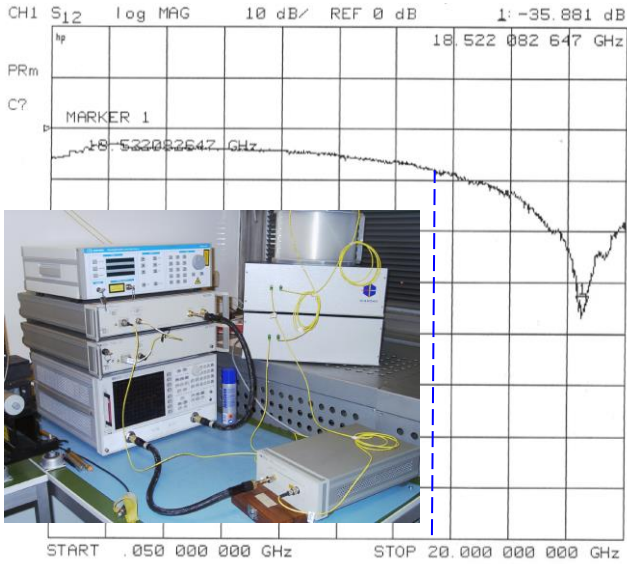


Fig. 5. The experimental laboratory setup and magnitude of S_{21} parameter, measured with $L=10$ km fiber, $f_{RF,rej,1}=18.522$ GHz.

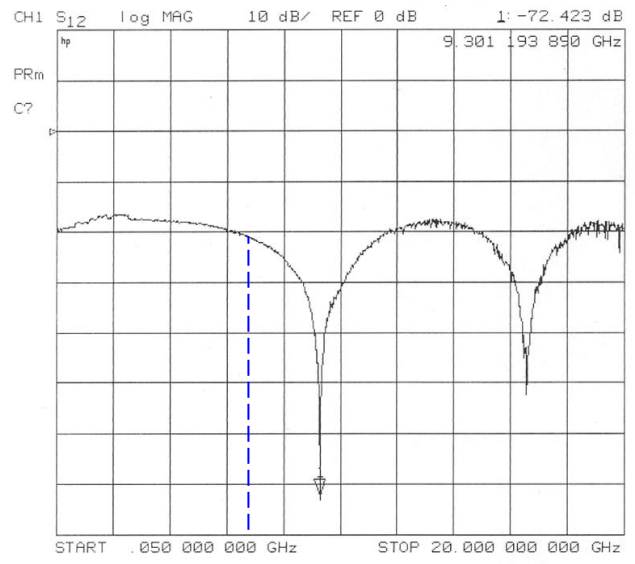


Fig. 8. Magnitude of S_{21} parameter, measured with $L=40$ km fiber, $f_{RF,rej,1}=9.301$ GHz, $f_{RF,rej,2}\approx 16.5$ GHz.

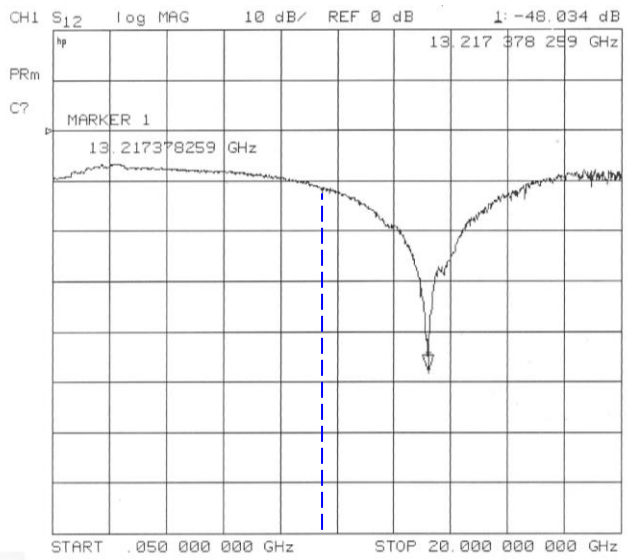


Fig. 6. Magnitude of S_{21} parameter, measured with $L=20$ km fiber, $f_{RF,rej,1}=13.217$ GHz.

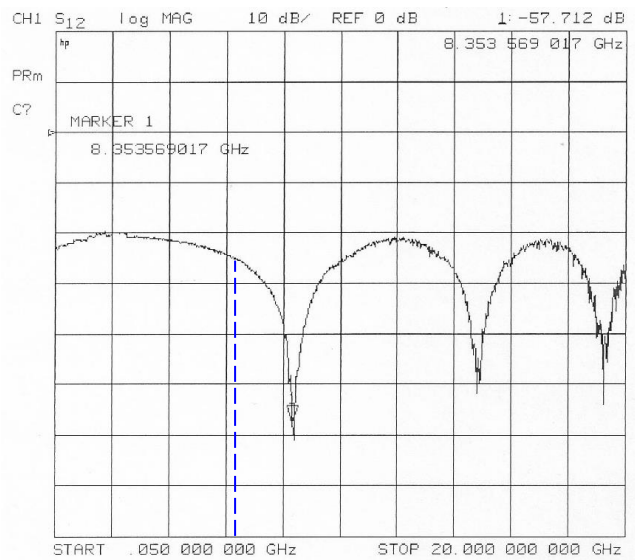


Fig. 9. Magnitude of S_{21} parameter, measured with $L=50$ km fiber, $f_{RF,rej,1}=8.353$ GHz, $f_{RF,rej,2}\approx 14.9$ GHz, $f_{RF,rej,3}\approx 19.2$ GHz.

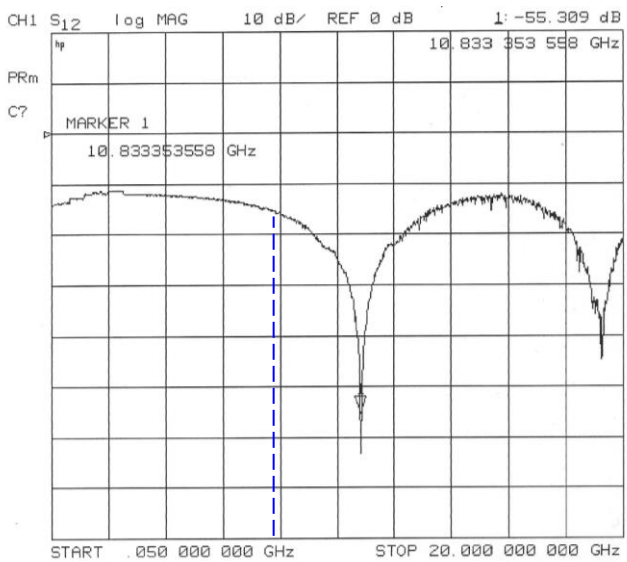


Fig. 7. Magnitude of S_{21} parameter, measured with $L=30$ km fiber, $f_{RF,rej,1}=10.833$ GHz, $f_{RF,rej,2}\approx 19.3$ GHz.

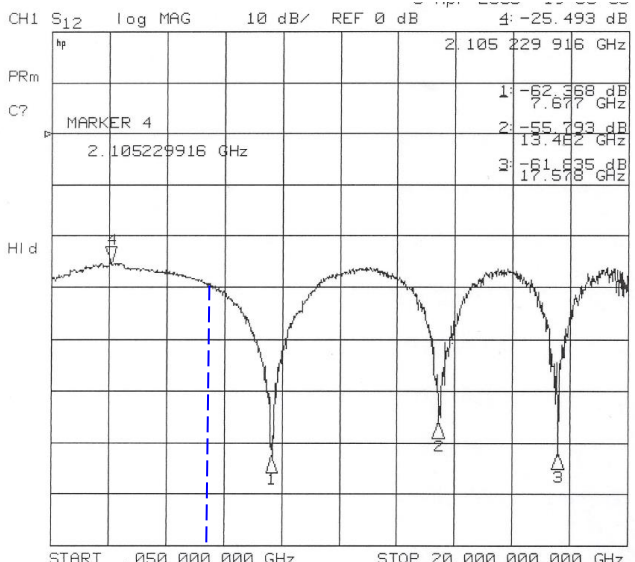


Fig. 10. Magnitude of S_{21} parameter, measured with $L=60$ km fiber, $f_{RF,rej,1}=7.677$ GHz, $f_{RF,rej,2}\approx 13.482$ GHz, $f_{RF,rej,3}\approx 17.578$ GHz.

V. MEASUREMENT OF RF SIGNAL TRANSMISSION

The Agilent Vector Network Analyzer was extended with a Hewlett-Packard (HP) Lightwave Test Set [4],[23],[30],[37]-[42] and used for swept analog RF measurements. Connecting 10 km, 20 km and 30 km long standard singlemode fiber-rolls to each other, systematic IM/DD transmission measurements have been performed. With 10 km steps, $L = 10, 20, 30, 40, 50$ and 60 km SSMF lengths have been tested. The magnitudes of S_{21} parameter are plotted in Fig. 5-10. The calculated 3 dB electrical bandwidth (as in equation (10) and in Table I) is marked with blue dashed line in each plot. The photo insert in Fig. 5 shows the laboratory test setup. The 1550 nm HP83424A lightwave CW source [39] was connected to the HP83422A lightwave modulator instrument [38]. For the O/E conversion the HP11982A lightwave converter instrument was used [41].

VI. SYSTEM CONSIDERATIONS

Several proposals have been reported for the generation and optical distribution of microwave and millimeter-wave carrier signals [4],[6],[10],[18]-[23],[44]. Stable, digitally programmable and low phase noise local oscillator (LO) signals are required at the μ W/mmW transceiver (TRX) points (Fig. 11 and the radio nodes in Fig.1). The μ W/mmW LO signal generation can happen locally at the TRX locations or remotely e.g. in a central point [21]. The optical network distributes the digital Gbps and GbE baseband signals. It seems to be a straightforward solution to reduce system complexity and costs by generating the μ W/mmW carriers centrally and distribute to the radio nodes over the same optical-fiber network that delivers the baseband Gbps or GbE digital signals. However, as discussed in this paper, chromatic dispersion effects raise significant limitations on system level. The optical signal distribution works efficiently only for short fiber-optical links and for relatively low carrier frequencies, as it is visible in Fig. 3-4. For the 60, 80 or 130 GHz bands the optical distribution is strongly limited by chromatic dispersion of the single-mode fiber. For example, carrier distribution of 60 GHz with regards to chromatic dispersion penalty is limited to about $L = 1$ km fiber length between the central station and the radio nodes. For 80 GHz, the carrier signal distribution is limited approximately to 500 meters, and for 130 GHz to approximately 200 meters. However, fiber-optical links of 5 - 20 km are typical even in dense urban networks. Dispersion compensating or dispersion shifted fibers (e.g. ITU-T G.655 [45]) would add additional complexity and attenuation to the network. Since coherent techniques [36] opened the possibility for digital signals to compensate chromatic dispersion electronically, telecom operators prefer to use and deploy SSMF (e.g. specified by ITU-T G.652.D [46]).

A possible solution to overcome these difficulties is to use sub-harmonic reference signals [23]. Sub-harmonic signals can be distributed optically with negligible dispersion penalty. At the radio node the sub-harmonic signal can be used as reference for the mmW synthesizer/LO to generate the required mmW carrier signal. The great advantage of such optically supported mmW synthesizers is that the TRX frequencies can be digitally set (programmed and if later required re-set) according to the radio channel arrangements. Unfortunately the disadvantage remains that each TRX needs its own local electronic circuitry, so the overall system deployment costs cannot be significantly reduced. Another important aspect is how the mmW carriers are generated. The two main alternatives are the electrical and the optical generation of the mmW signals. In actual 4G/5G systems electrical methods are dominating for the mmW local oscillator

and carrier signal generation. Even though intensive research has started nearly three decades ago for optical mmW carrier generation methods [3]-[6],[15],[22], in commercial networks the typical scenario remained the local electrical generation of the 26...80 GHz carriers [18],[26]. This research is continuously ongoing, forecasting smaller size and reduced power consumption equipment, (i.e. sustainable products) as well as targeting more cost-effective solutions [3],[19]-[25],[36]. Optical heterodyning techniques can beat mmW signals using optical waves [4],[44]. As traditional frequency bands (up to 80 GHz) are getting saturated, in future B5G/6G systems new mmW and sub-THz links (e.g. D-band: ~ 130 GHz) will support the mobile anyhaul, beside the legacy frequency bands [10],[15],[28]. Furthermore, an extremely intensive utilization of meshed optical-fiber and hybrid mmW/FSO networks is expected too [1]-[13],[15],[18]-[23],[43],[46]-[48]. These trends will bring optical carrier generation techniques for mmW, sub-THz and even for FSO links to reality from both technical and economic points of view [21],[24],[25].

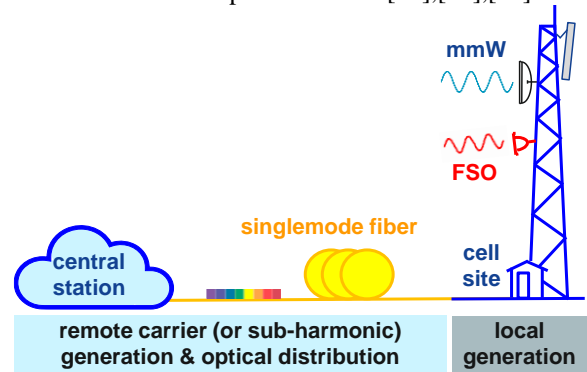


Fig. 11. Generation and distribution of μ W and mmW carriers

VII. CONCLUSIONS

In the recent decades, a significant breakthrough has been observed in microwave and millimeter-wave photonics applied for carrier generation and for hybrid fiber/wireless distribution of high bit-rate data. Advanced telecommunication networks demand enormous throughputs. Extremely high data rates are required in mobile 4G, 5G, and in future 6G systems, as well as in data centers and in cloud-core networks. To support such high data rates wider bandwidths are necessary in the anyhaul networks. Higher mmW carriers (e.g. in D-band) and FSO links can support these demands. In this paper the limitation of chromatic dispersion has been investigated. The theoretical formulas have been verified experimentally by systematic measurements of several km long optical fibers. It was shown that chromatic dispersion penalty must be considered in hybrid optical-wireless networks. Therefore in future 6G systems such carrier generation methods have excellent prospectives that do not suffer from chromatic dispersion limitations.

REFERENCES

- [1] P.J.Winzer, D.T.Neilson, A.R.Chraplyvy, "Fiber-optic transmission and networking: the previous 20 and the next 20 years", *Optics Express*, Vol.26, No.18, pp.24190-24239, 2018. DOI: 10.1364/OE.26.024190
- [2] Nokia, "400G Everywhere", e-book, Espoo, Finland, May 2021.
- [3] I.Frigyes, "Optical/Photonic Techniques for Antenna Beamforming in Wireless Communications", (in Hungarian: Optikai-fotonikai technikán alapuló nyalábalakítás a vezeték nélküli hírközlésben), *Napkút Kiadó*, ISBN: 978-615-6555-70-0, Budapest, Hungary, 2023. <http://hdl.handle.net/10890/52264>
- [4] A.Hilt, "Optical Transmission and Processing of Signals in Microwave Telecommunication Systems, Ph.D. dissertation, INPG, Grenoble, France, May 1999. <http://hdl.handle.net/10890/17025>
- [5] G.Járó, "High speed optical receivers", (in Hungarian: Nagysebességű optikai vevők), Ph.D. dissertation, BME, Technical University of Buda-

- pest, Budapest, Hungary, June 1999. <http://hdl.handle.net/10890/17030>
- [6] M.A.Ilgaz, A.Lavrič, B.Batagelj, "Phase-noise degradation of an optically distributed local oscillator in a radio access network", *Radio-engineering*, Vol.30, No.1, pp.10-15, 2021. DOI: 10.13164/re.2021.0010
 - [7] E.Agrell, M.Karlsson, A.R.Chraplyvy, D.J.Richardson, et al., "Roadmap of optical communications", *Journal of Optics*, Vol.18, 063002, pp.1-40, May 2016. DOI: 10.1088/2040-8978/18/6/063002
 - [8] A.Hilt, A.Farkasvölgyi, M.L.Iványi, "Experimental Verification of Transmittance and Harmonics in External Optical Intensity Modulation", *IEEE 34th International Conference Radioelektronika*, Zsolna, Slovakia, April 2024. DOI: 10.1109/RADIOELEKTRONIKA61599.2024.10524077
 - [9] H-H.Lu, C-Y.Li, X-H.Huang, C-J.Lin, R-D.Lin, Y-S.Lin, Y-S.Tang, W-C.Fan, "A combined fibre/free-space-optical communication system for long-haul wireline/wireless transmission at millimetre-wave/sub-THz frequencies", *Springer Nature, Communications Engineering*, Vol.2, No.18, pp.1-8, May 2023. DOI: 10.1038/s44172-023-00068-1
 - [10] H-H.Lu, C-Y.Li, W-S.Tsai, P-S.Chang, Y-T.Chen, C-X.Liu, T.Ko, Y-Y.Lin, "Simultaneous Transmission of 5G MMW and Sub-THz Signals Through a Fiber-FSO-5G NR Converged System", *Journal of Lightwave Technology*, Vol.40, No.8, pp.2348-2356, April 2022. DOI: 10.1109/JLT.2021.3139620
 - [11] A.Hilt, G.Járó, A.Zólomy, B.Cabon, T.Berceli, T.Marozsák, "Microwave characterization of high-speed pin photodiodes", *9th Conference on Microwave Techniques, COMITE'1997*, pp.21-24, Pardubice, Czech Republic, Oct. 1997. <http://hdl.handle.net/10890/15803>
 - [12] K.Sun, A.Beling, "High-Speed Photodetectors for Microwave Photonics", *Applied Sciences*, Vol.9, No.4, p.623, pp.1-15, Feb. 2019. DOI: 10.3390/app9040623
 - [13] N.Badraoui, T.Berceli, "An experimental millimeter wave radio over fiber link with double polarization multiplexing", *Optical and Quantum Electronics*, Vol.53, No.9, paper 533, pp.1-9, 2021. DOI: 10.1007/s11082-021-03178-2
 - [14] A.Hilt, G.Járó, A.Farkasvölgyi: "Capacity and Performance Test Methods for Cloud-based Telecommunication Network Functions", *Radioelektronika'2025*, Hnanice, Czech Republic, May 2025.
 - [15] I.Frigyes, L.Csurgai-Horváth, "Free-Space Optics and E-band Radio: Complementary Techniques for Gbit/sec Wireless", *IEEE Wireless Communication and Networking Conference Workshops*, Sydney, Australia, 2010. DOI: 10.1109/WCNCW.2010.5487647
 - [16] A.Hilt and L.Pozsonyi, "Application of Fiber-Optical Techniques in the Access Transmission and Backbone Transport of Mobile Networks", *Fiber and Integrated Optics*, Vol.31, No.5, pp.277-298, 2012. DOI: 10.1080/01468030.2012.723797
 - [17] IEEE Standard for Ethernet, Std 802.3by-2016, Amendment 2: Media Access Control Parameters, Physical Layers, and Management Parameters for 25 Gb/s Operation, p.235, *IEEE Computer Society, LAN/MAN Standards Committee*, New York, USA, June 2016.
 - [18] A.Hilt, J.Varga, G.Járó, "Availability-Aware E-band Wireless Extension of Fiber-Access", *IEEE/IFIP Network Operations and Management Symposium, NOMS'2022*, Budapest, Hungary, April 2022. DOI: 10.1109/NOMS54207.2022.9789802
 - [19] K.V.Baliž, A.Debevc, M.Vidmar, B.Batagelj, "Analog Wavelength Locking in an Optical Single-Sideband Transmitter of a Millimeter-Wave Radio-Over-Fiber Link Featuring a Micro-Ring Resonator and a Heat-Pump-Controlled Laser", *Photonics*, Vol.10, p.1341, Dec. 2023. DOI: 10.3390/photonics10121341
 - [20] T.Berceli, E.Udvary, A.Hilt, "A New Equalization Method for Dispersion Effects in Optical Links", *10th International Conference on Transparent Optical Networks, ICTON'2008*, Vol.4, pp.98-101, Athens, Greece, June 2008. DOI: 10.1109/ICTON.2008.4598743
 - [21] M.A.Ilgaz, A.Lavrič, B.Batagelj, M.Vidmar, "Centralized Millimeter-Wave Opto-Electronic Oscillator", *2020 Photonic North*, Niagara Falls, Canada, May 2020. DOI: 10.1109/PN50013.2020.9166975
 - [22] G.Maury, et al., "Remote upconversion in microwave fiber-optic links employing an unbalanced Mach-Zehnder interferometer", *SPIE 44th Conference on Terahertz and Gigahertz Photonics*, Vol.3795, pp.468-476, Denver, Colorado, USA, July 1999. DOI: 10.1117/12.370195
 - [23] A.Hilt, A.Vilcot, T.Berceli, T.Marozsák, B.Cabon, "New carrier generation approach for fiber-radio systems to overcome chromatic dispersion problems", *IEEE MTT Symposium*, pp.1525-1528, Baltimore, USA, June 1998. DOI: 10.1109/MWSYM.1998.700665
 - [24] C.J.Bouras, "Analyzing mmWave Bands from a Techno-Economic Perspective in 5G Networks", *International Journal of Business Data Communications and Networking* Vol.19, No.1, Dec. 2024. DOI: 10.4018/IJBDCN.361890
 - [25] Y.Aragane, "Innovative Optical and Wireless Network (IOWN) for a Sustainable World", *Optical Fiber Communications Conference, OFC'2023*, San Diego, USA, May 2023. DOI: 10.1364/OFC.2023.Tu2A.4
 - [26] A.Hilt, "Throughput Estimation of K-zone Gbps Radio Links Operating in the E-band", *Informacije MIDE M, Journal of Microelectronics, Electronic Components and Materials*, Vol.52, No.1, pp.29-39, 2022. DOI: 10.33180/InfMIDEM2022.104
 - [27] A.Farkasvölgyi, I.Frigyes, "Modulation Schemes for Long Distance Optical Communication", *Photonics and Electromagnetics Research Symposium, PIERS'2019*, Rome, Italy, June 2019. DOI: 10.1109/PIERS-Spring46901.2019.9017305
 - [28] A.Hilt, "Feasibility of D-band Fixed Radio Links for 5G and Beyond Access Networks", *IEEE 34th International Conference Radioelektronika*, Zsolna, Slovakia, April 2024. DOI: 10.1109/RADIOELEKTRONIKA61599.2024.10524063
 - [29] D.Marcuse, C.Lin, "Low Dispersion Single-Mode Fiber Transmission-The Question of Practical versus Theoretical Maximum Transmission Bandwidth", *IEEE Journal of Quantum Electronics*, Vol.QE-17, No.6, June 1981. DOI: 10.1109/JQE.1981.1071236
 - [30] A.Hilt, "Microwave harmonic generation in fiber-optical links", *Journal of Communications and Information Technology*, Part 2, pp.22-28, Warsaw, Poland, 1/2002. <http://hdl.handle.net/10890/15602>
 - [31] O.Terra, "Chromatic dispersion measurement in optical fibers using optoelectronic oscillations", *Optics and Laser Technology*, Vol.115, pp. 292-297, 2019. DOI: 10.1016/j.optlastec.2019.02.037
 - [32] A.Hilt, E.Udvary, et al., "Harmonic Components and Dispersion of Mobile Network Signals due to Fiber-Optical Transmission", *IEEE Optical Network Design and Modelling Conference, ONDM'2017*, Budapest, Hungary, May 2017. DOI: 10.23919/ONDM.2017.7958543
 - [33] S.Nakahara, "Technologies and Services of Digital Broadcasting (8), Modulation Systems (part 1)", *Broadcast Technology No.14*, pp.10-17, Spring 2003.
 - [34] M.Forghani, B.Razavi, "Circuit Bandwidth Requirements for NRZ and PAM4 Signals", *IEEE International Symposium on Circuits and Systems, ISCAS'2022*, pp.990-994, Austin, USA, June 2022. DOI: 10.1109/ISCAS48785.2022.9937588
 - [35] I.Frigyes, A.Hilt, S.Csemyin, "Investigations in Microwave Optical Links – Accent on QAM", *IEEE International Topical Meeting on Microwave Photonics, MWP'2000*, pp.156-159, Oxford, UK, Sept. 2000. DOI: 10.1109/MWP.2000.889811
 - [36] K.Kikuchi, "Fundamentals of Coherent Optical Fiber Communications", *Journal of Lightwave Technology*, Vol.34, No.1, pp.157-179, Jan. 2016. DOI: 10.1109/JLT.2015.2463719
 - [37] Agilent 87441 Family of Filters, Product Overview, 5964-3865E, 1995.
 - [38] Hewlett Packard, HP83422A Lightwave Modulator, User's Guide.
 - [39] Hewlett Packard, HP83424A Lightwave CW Source, User's Guide.
 - [40] A.Hilt, T.Berceli, E.Udvary, "Microwave Network Analysis Extended to Optical Systems", *COMITE'2005*, Prague, Czech Republic, Sept. 2005. <http://hdl.handle.net/10890/15683>
 - [41] Agilent 11982A Amplified Lightwave Converter Operation and Service Manual, Agilent Part No. 11982-90014, pp.1-68, USA, HP July 2000. [Online accessed: Jan. 2025] https://xdevs.com/doc/HP_Agilent_Keylight/HP%2011982A%20Operation%20&%20Service.pdf
 - [42] A.Hilt, "Basics of Microwave Network Analysis of Optical Circuits", *MoiKIT Optical-Wireless Workshop*, Budapest, Hungary, March 2001. <http://hdl.handle.net/10890/16316>
 - [43] E.Babics, É.Csákány, T.Jakab, R.Konkoly, L.Szandi, "Operational Databases-related Multi-Layer Network Modeling to Support Network Development at Magyar Telekom", *IEEE 13th International Telecommunications Network Strategy and Planning Symposium, Networks'2008*, pp.1-8, Budapest, Hungary, Sep. 2008. DOI: 10.1109/NETWKS.2008.6231339
 - [44] A.W.M.Mohammad, "Integrated photonics for millimetre wave transmitters and receivers", *Ph.D. dissertation, University College London*, London, UK, February 2019.
 - [45] Rec. ITU-T G.655 (11/2009), "Transmission systems and media, digital systems and networks, Transmission media and optical systems characteristics – Optical fibre cables, Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable", *International Telecommunication Union*, 2009.
 - [46] Rec. ITU-T G.652 (08/2024), "Transmission systems and media, digital systems and networks, Transmission media and optical systems characteristics – Optical fibre cables, Characteristics of a single-mode optical fibre and cable", *International Telecommunication Union*, 2024.
 - [47] A.Farkasvölgyi, L.Csurgai-Horváth, A.Hilt, "High Resolution Rain Intensity Measurement and its Application on Free Space Optics", *Journal of Microelectronics, Electronic Components and Materials, Informacije MIDE M*, Vol.54, No.3, pp.167-175, DOI: 10.33180/InfMIDEM2024.301
 - [48] M.Adel, H.Seleem, M.Nasr, H.El-Khobby, "Transmission of 128 Gb/s Optical QPSK Signal over FSO Channel under Different Weather Conditions and Pointing Errors", *Journal of Physics: Conference Series*, 1447, 012055, 2020. DOI: 10.1088/1742-6596/1447/1/012055