An Improved Configuration for Radio over Fiber Transmission

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Abstract: A configuration for radio-over-fiber transmission, with remote LO delivery from the central office, and a simple, cost-effective, base station solution is proposed. It is shown that, using practically available components, and even with a fiber dispersion of 17 *ps/nm/km*, it is possible to transmit, without repeaters, bit rates of up to 622 *Mbit/s* for about 20 *km* at a bit-error rate of 10^{-9}, with 0dBm laser power and a modest optical gain of 6dB. By increasing the optical gain to 25 dB, the link length can be increased to ~80 km.

1. Introduction

Future broadband mobile services are expected to be based on pico-cellular networks and will require a very large number of base stations (BS's) that are expected to operate at millimeter wave frequencies. Because of high attenuation at these frequencies, connecting the BS's to the central office (CO) by using radio links will place serious limitations on the allowed repeater-less distance. Optical links can alleviate this problem while "radio-over-fiber" (ROF) via optical heterodyning potentially allows simplification of BS design [1]. Chromatic-dispersion limitations for broadband transmission can also be mitigated, for example, by using optical and electronic single-side-band modulation [2], or base band over fiber possibly with remote local-oscillator delivery [3]. The latter, however, requires a modulator/ multiplexer at each BS, while the former is based on a millimetre-wave local oscillator at the BS. Clearly, both approaches increase the complexity of the BS making it less cost effective.

One solution that addresses the above problems is based on the use of two single-electrode Mach-Zehnder modulators [4] such that remote LO delivery and data transmission via mm-wave over fiber are realized simultaneously. However, a Fabry-Perot (FP) filter is required to remove one of the optical side bands. This FP filter should have a large quenching ratio and needs to be well controlled to prevent the appearance of a vestigial side band. The phase noises of the optical components in the two optical paths might also be partially de-correlated leading to some broadening of the millimeter wave and a consequent carrier-to-noise-ratio (CNR) penalty [5]. In addition, because of the additional loss introduced by the FP, a custom-made asymmetric combiner is needed to equalize the total optical power of the two paths. The reported performance of this system is a repeater-less transmission of 622 Mbit/s over 15 km (BER=10^{-9}) for a high laser output of 11dBm.

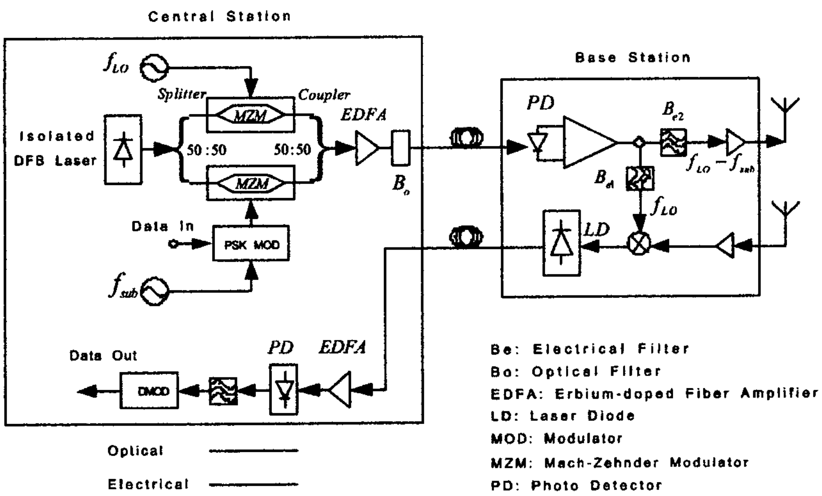

Fig. 1. Configuration of the proposed radio-over-fiber system.

In this paper we propose an improved ROF configuration and present the performance of our design in the presence of amplified spontaneous emission (ASE), fiber chromatic dispersion, and laser phase noise. An erbium-doped fiber amplifier (EDFA) has been used to cancel, in the first instance, the effect of optical transmitter losses. We find that by using components with realistic even modest specifications, and a relatively large chromatic-dispersion fiber, a repeater-less link of about 20 *km* is feasible, for data rates in excess of 622 *Mbit/s* at a bit-error rate less than 10^{-9} for a laser power of 0dBm and an optical gain of 6dB. Compared to the system of [4], no FP filter is needed in our configuration to remove the redundant optical side band, and our scheme requires much less optical power to achieve the same BER level, and introduces less ASE noise because of the system's smaller optical bandwidth.

2. System Configuration

Fig. 1 shows the schematic diagram of the proposed optical mm-wave link and the modulation scheme used. The output of an isolated DFB laser is coupled into two dual-electrode Mach-Zehnder modulators in parallel by a standard 3-dB optical power splitter. The upper MZM is driven by a millimeter-wave signal at frequency of f_{LO} and is configured to produce optical single-side band modulation. It therefore generates the original optical spectral component at f_{opt} as well as an optical wave upshifted by f_{LO}. The lower MZM is driven by a BPSK data sub-carrier and is also configured for optical single-side band modulation; it therefore generates the original optical frequency at f_{opt} and a modulated optical single side band at $f_{opt}+f_{sub}$. A second 3-dB optical power coupler combines the output of the two MZM's and couples one output branch to an optical amplifier. Fig. 2 shows the spectrum at the output of the coupler. The spectrum has been tailored such that the cellular-radio wave (beat) component (at frequency of f_{LO}-f_{sub}) can be directly filtered out for electronic power amplification and radio transmission within the cells. The designed spectrum also yields a relatively "clean" local oscillator millimetre-wave component (at frequency of f_{LO}) for down-conversion of user signals for transmission on the optical uplink.

The foregoing tailoring is based on the use of the dual-electrode MZ modulator configured for OSSB modulation as shown in Fig. 3. Both MZM's are driven at their quadrature-bias points to minimize operational non-linearities. In order to obtain the required single sideband modulation, the normalized bias voltages of the two MZM's are set equal to 1/2, and the normalized modulating voltages of MZM's are set much less than 1/δ to reduce the effects of higher-order harmonics. The output of the laser is given by Eq. (1), while the outputs of the upper and lower MZM are given by Eq. (2) and Eq. (3), respectively.

$$E_{LD}(t)=\sqrt{2P_{opt}}\cos(\varpi_{opt}t), \qquad (1)$$

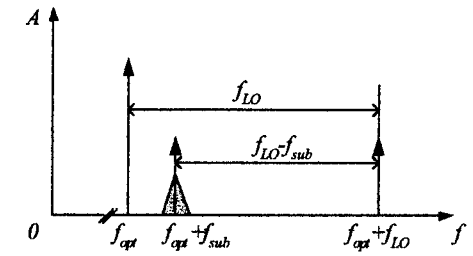

Fig. 2. Optical spectrum of the output of the coupler.

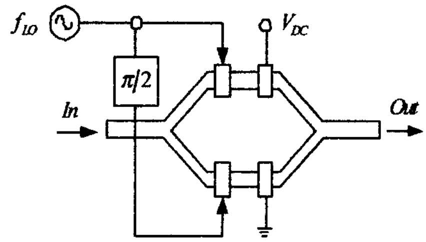

Fig. 3. Configuration of the dual-electrode MZM for single sideband generation.

$$E_{upp}(t)=\frac{\sqrt{P_{opt}/I_C I_M}}{2}J_0(\beta_{LO}\pi)\cos\left(\varpi_{opt}t+\frac{\pi}{4}\right) -\sqrt{\frac{P_{opt}}{I_C I_M}}J_1(\beta_{LO}\pi)\cos[(\varpi_{opt}+\varpi_{LO})t], \qquad (2)$$

$$E_{low}(t)=\frac{\sqrt{P_{opt}/I_C I_M}}{2}J_0(\beta_{sub}\pi)\cos\left(\varpi_{opt}t+\frac{\pi}{4}\right) -\sqrt{\frac{P_{opt}}{I_C I_M}}J_1(\beta_{sub}\pi)\cos[(\varpi_{opt}+\varpi_{sub})t+\varphi_{sig}(t)], \qquad (3)$$

In the above, P_{opt} is the output power of the DFB laser, ϖ_{opt} is the angular frequency of the light wave, I_M is the insertion loss of each MZM, I_C is the insertion loss of the coupler, ϖ_{LO} is the angular frequency of the millimeter-wave signal for remote LO delivery, ϖ_{sub} is the angular frequency of the BPSK data carrier, $\beta_{LO}(=V_{ac-LO}/V_\pi)$ is the normalized modulation voltage of the upper MZM, $\beta_{sub}(=V_{ac-sub}/V_\pi)$ is the normalized modulation voltage of the lower MZM, V_π is the switching voltage of the MZM, $J_n()$ is the n-th Bessel function of the first kind, $\varphi_{sig}(t)$ is the BPSK data, such that $\varphi_{sig}(t)=0$ for binary "1" and $\varphi_{sig}(t)=\pi$ for binary "0".

One Erbium-doped amplifier (EDFA) is used to compensate for the optical loss introduced by the optical coupler, and the MZM's, and if required also the fiber loss. The EDFA produces amplified spontaneous emission (ASE), so that an optical filter is used to attenuate the out-of-band ASE noise components. The electrical field at the output of the fiber is given by [1]:

$$
\begin{aligned}
E_{PD}(t) = & \sqrt{\frac{GP_{opt}}{2I_M I_C I_F L}}\{J_0(\beta_{sub}\pi)+J_0(\beta_{LO}\pi)\}\cos\left\{\varpi_{opt}t+\frac{\pi}{4}\right\} \\
& -\sqrt{\frac{GP_{opt}}{I_M I_C I_F L}}J_1(\beta_{sub}\pi)\cos\{(\varpi_{opt}+\varpi_{sub})t+\varphi_{sig}(t)\} \\
& -\sqrt{\frac{GP_{opt}}{I_M I_C I_F L}}J_1(\beta_{LO}\pi)\cos\{(\varpi_{opt}+\varpi_{LO})t\} \\
& +\sum_{k=-\frac{B_o}{2\delta f}}^{\frac{B_o}{2\delta f}}\sqrt{\frac{2N_{sp}(G-1)hf_{opt}\delta f}{I_F L}}\cos\{(\varpi_{opt}+2\pi k\delta f)t+\Omega_k\}
\end{aligned}
\quad ,(4)
$$

where G is the gain of the EDFA, I_F is the insert loss of the optical filter, L is the fiber loss, N_{sp} is the spontaneous emission factor of the EDFA, hf_{opt} is the photon energy, Ù$_k$ is the phase of ASE noise component, and B_o is the bandwidth of optical filter.

At the base station, a broadband photo diode (PD) detects the optical signal given in Eq. (4). Because of the square-law characteristic of the PD, the optical components beat with each other resulting in electrical signals at corresponding beat frequencies. Two band-pass filters filter out the generated BPSK data carrier at a frequency of $f_{LO}-f_{sub}$ and the recovered electrical local oscillator at frequency f_{LO}, respectively. The data carrier is amplified directly and radiated out to the cells, while the LO is used for down-conversion of the uplink carrier. As can be seen in Fig. 1, a very simple BS structure is thus achieved.

3. Link Performance

The two middle terms of Eq. (4) produce the mm-wave data-carrying signal given by Eq. (5) below, while the beat component produced by the first and third terms yields the electrical LO component given by Eq. (6).

$$
\begin{aligned}
i_s(t) = & \frac{\eta e G P_{opt}}{hf_{opt} I_M I_C I_F L} J_1(\beta_{sub}\pi) J_1(\beta_{LO}\pi) \\
& \cdot \cos\{(\varpi_{LO}-\varpi_{sub})t-\varphi_{sig}(t)\}
\end{aligned}
\quad , \qquad (5)
$$

$$
\begin{aligned}
i_{LO}(t) = & \frac{\eta e G P_{opt}}{\sqrt{2}hf_{opt} I_M I_C I_F L}\{J_0(\beta_{sub}\pi)+J_0(\beta_{LO}\pi)\} \\
& \cdot J_1(\beta_{LO}\pi)\cos\left(\varpi_{LO}t-\frac{\pi}{4}\right)
\end{aligned}
\quad , \qquad (6)
$$

In the above, e is the electronic charge and η is the quantum efficiency of the PD.

After de-modulation of the BPSK data, the bit error probability is given by:

$$
P_e = \frac{1}{2} erfc\left(\sqrt{\frac{P_s}{N(f)R_b P_x}}\right), \qquad (7)
$$

where P_S is the signal power obtained from Eq. (5), R_b is the bit rate of BPSK data, $N(f)$ is the power spectral density of the total noise (including ASE noise, thermal noise and shot noise), P_x is the C/N penalty due to fiber dispersion and laser phase noise and given by Eq. (8).

$$
P_x = \exp(2\pi\Delta\upsilon\Delta\tau), \qquad (8)
$$

$$
\Delta\tau = \frac{D\cdot L_f\cdot\lambda^2\cdot\Delta f}{c}. \qquad (9)
$$

In the above, $\Delta\upsilon$ is the 3-dB linewidth of the laser output, $\Delta\tau$ is the delay difference between the two optical side bands due to fiber chromatic dispersion. In Eq. (9), D is the chromatic dispersion parameter of the optical fiber, L_f is the fiber length, λ is the optical wavelength, and Δf is the frequency difference between the two optical side bands.

The BER for the recovered BPSK data is shown in Fig. 4 (a) as a function of received optical power. The salient parameters are: P_{opt} = 0dBm, $L = 3$ *dB*, $G = 6$ *dB*, $I_M = 2.7$ *dB*, $I_C = 3dB$, $I_F = 0.3dB$, $\beta_{sub}(\beta_{LO}) = 0.08$, $f_{LO} = 60$ *GHz*, $f_{cell} = 2.5$ *GHz*, $B_o = 100$ *GHz*, ç = 0.9, $N_{SP} = 2.75$, $R_b = 622$ *Mbit/s*, optical wavelength $\lambda = 1550$ *nm*, fiber dispersion coefficient $D = 17$ *ps/nm/km*, and fiber loss coefficient is 0.3 *dB/km*. Fig. 4 (b) shows the BER as a function of the transmission distance. Fiber chromatic dispersion and laser phase noise broaden the spectrum of the recovered millimetre-wave carrier thus reducing the amplitude and worsening the carrier to noise ratio as a function of distance. As can be seen from Fig. 4 (b), the carrier with a laser line width of 1 *MHz* can be successfully transmitted more than 20 *km* with a BER less than 10^{-9}, while in the case of laser line widths of 75 *MHz* and 150 *MHz* the maximum transmission distances are reduced to 19 *km* and 18 *km*, respectively. Fig. 4 (c) shows the maximum transmission distance as a function of output power of the laser at BER of 10^{-9}, and again for an optical gain of 6 dB. The results are consistent with those in Fig. 4 (b).

From the foregoing, it should be clear that the maximum transmission also depends on the gain of the EDFA. This is shown in Fig. 4 (d), from which we see that by increasing the gain to , say, 25 dB, the distance increases to about 80 km.

4. Conclusion

We have proposed and presented the performance of a feasible configuration for radio-over-fiber transmission with cost-effective remote LO delivery from the central office. We show that, with practically available components and 0 dBm transmitted optical power, 622 *Mbit/s* data can be transmitted about 20 *km* (without repeaters) at a bit-error rate of less than 10^{-9}, even when using a relatively high dispersion fiber and an optical gain of only 6 dB. If the gain is increased to 25 dB, the maximum repeater-less link length can be increased to approximately 80 km.

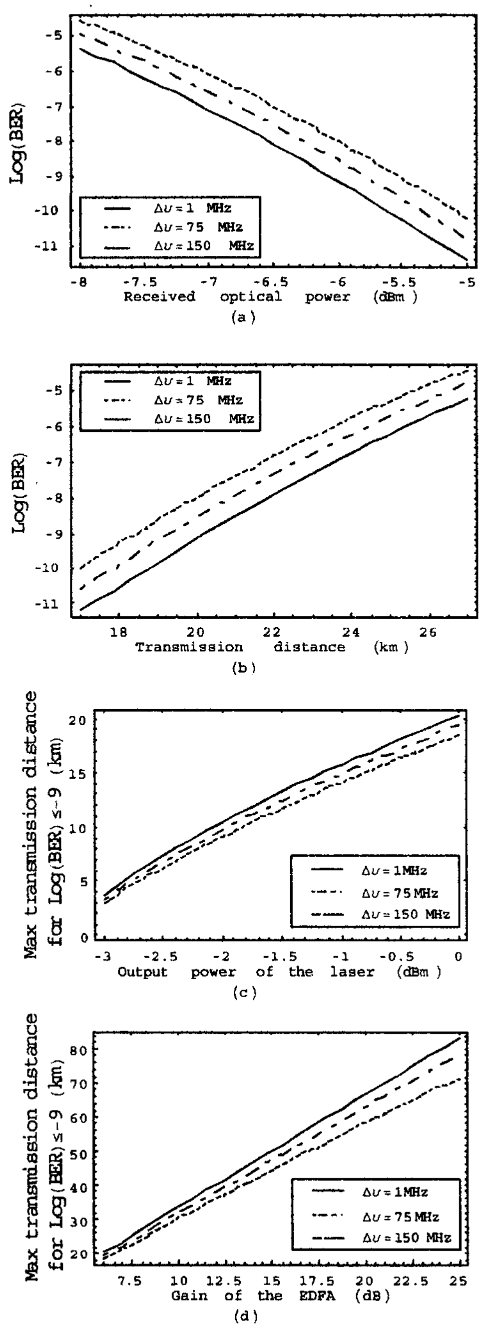

Fig. 4. Performance of 622Mbit/s BPSK data transmission, (a) BER for the recovered data as a function of received optical power, (b) BER for the recovered data as a function of transmission distance, (c) Maximum transmission distance as a function of the output power of the laser at a BER of 10^{-9}. (d) Maximum transmission distance as a function of the EDFA gain at a BER of 10^{-9}. In all four cases, $\Delta\upsilon$ is the laser line width.

References

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