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APPENDIX A

MODULATOR AND DEMODULATOR STRUCTURE

A.1 INTRODUCTION

In this appendix a discussion of an OM-OFDM modulator and OM-OFDM demodulator structure will be presented. Throughout this appendix various figures (Fig. A.1 and Fig. A.2), which represent the OM-OFDM modulator and OM-OFDM demodulator structure and the subsequent positions there-in will be discussed.

A.2 MODULATOR STRUCTURE

As previously discussed, consider the discrete complex output of an N-point IFFT OFDM signal, given by

$$m_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j\frac{2\pi nk}{N}}, \qquad n = 0, 1, \ldots\ldots, N-1 \tag{A.1}$$

$$= \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} (a_k + jb_k) \cdot \left(\cos\left(\frac{2\pi nk}{N}\right) + j\sin\left(\frac{2\pi nk}{N}\right)\right). \tag{A.2}$$

In Eq (A.1), X_k represents the complex signal, which may also be written as $a_k + jb_k$. This signal may be modulated using the method which follows.

$$\Phi_{1n} = \frac{\Re(m_n)}{\varsigma} = \frac{1}{\varsigma\sqrt{N}} \sum_{k=0}^{N-1} a_k \cos\left(\frac{2\pi nk}{N}\right) - b_k \sin\left(\frac{2\pi nk}{N}\right) \quad \text{and} \tag{A.3}$$

$$\Phi_{2n} = \frac{\Im(m_n)}{\varsigma} = \frac{1}{\varsigma\sqrt{N}} \sum_{k=0}^{N-1} b_k \cos\left(\frac{2\pi nk}{N}\right) + a_k \sin\left(\frac{2\pi nk}{N}\right). \tag{A.4}$$

Here $\Re$ and $\Im$, refer to the real and imaginary parts of the OFDM message signal, ς refers to a constant division term, whereas Φ_{1n} and Φ_{2n} represent the equivalent discrete real and imaginary OFDM phase mapping. The purpose of an OM-OFDM modulator is to transform the incoming complex OFDM message signal into the signal shown below

$$\cos(2\pi f_c t + \Phi_1(t) + \Psi_{os}) - \cos(2\pi f_c t + \Phi_2(t)) \tag{A.5}$$

where Ψ_{os} is an offset term, $\Phi_1(t)$ and $\Phi_2(t)$ represent the equivalent real and imaginary OFDM phase mapping. Applying the following identity [91]

$$\cos(z_1) - \cos(z_2) = 2\sin\left(\frac{z_2 - z_1}{2}\right) \cdot \sin\left(\frac{z_1 + z_2}{2}\right) \tag{A.6}$$

to Eq (A.5) results in

$$2\sin\left(\frac{\Phi_2(t) - \Phi_1(t) - \Psi_{os}}{2}\right) \cdot \sin\left(2\pi f_c t + \frac{\Phi_1(t) + \Psi_{os} + \Phi_2(t)}{2}\right). \tag{A.7}$$

In Fig. A.1, at 1 and 2, the incoming complex message signal is separated into its real

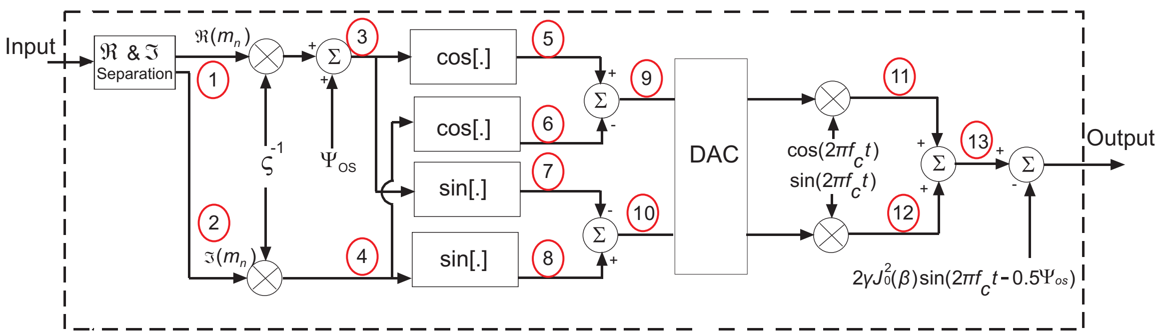

Figure A.1: OM modulator structure

(Eq (A.3)) and imaginary (Eq (A.4)) components. Thereafter, at 3, the signal can be expressed as $\Phi_{1n} + \Psi_{os}$ $\left(\text{where } \Phi_{1n} = \frac{\Re(m_n)}{\varsigma}\right)$. Similarly, the signal at 4 can be written as Φ_{2n} $\left(\text{where } \Phi_2 = \frac{\Im(m_n)}{\varsigma}\right)$. At 5, the signal can be expressed as $\cos(\Phi_{1n} + \Psi_{os})$. Similarly, at 6, the signal can be written as $\cos(\Phi_{2n})$. In addition, at 7 the signal can be represented as $\sin(\Phi_{1n} + \Psi_{os})$ and the signal at 8 can be written as $\sin(\Phi_{2n})$. At 9 the signal can be expressed as

$$\begin{aligned} & \cos(\Phi_{1n} + \Psi_{os}) - \cos(\Phi_{2n}) \\ = \;& -2\sin\left(\frac{\Phi_{1n} + \Psi_{os} + \Phi_{2n}}{2}\right)\sin\left(\frac{-\Phi_{2n} + \Phi_{1n} + \Psi_{os}}{2}\right). \end{aligned} \tag{A.8}$$

At 10, the expression can be written as

$$\begin{aligned} & \sin(\Phi_{2n}) - \sin(\Phi_{1n} + \Psi_{os}) \\ = \;& -2\sin\left(\frac{-\Phi_{2n} + \Phi_{1n} + \Psi_{os}}{2}\right)\cos\left(\frac{\Phi_{1n} + \Psi_{os} + \Phi_{2n}}{2}\right). \end{aligned} \tag{A.9}$$

The subsequent signals are passed through a digital-to-analog converter (DAC). Thereafter at 11, the expression can be shown to be

$$-2\sin\left(\frac{\Phi_1(t) + \Psi_{os} + \Phi_2(t)}{2}\right)\sin\left(\frac{-\Phi_2(t) + \Phi_1(t) + \Psi_{os}}{2}\right)\cdot\cos(2\pi f_c t). \tag{A.10}$$

The expression at 12 can be represented by

$$-2\sin\left(\frac{-\Phi_2(t) + \Phi_1 + \Psi_{os}}{2}\right)\cos\left(\frac{\Phi_1(t) + \Psi_{os} + \Phi_2(t)}{2}\right)\cdot\sin(2\pi f_c t). \tag{A.11}$$

Thereafter the signals from 11 and 12 are added to produce

$$\begin{aligned} & -2\sin\left(\frac{\Phi_1(t) + \Psi_{os} + \Phi_2(t)}{2}\right)\sin\left(\frac{-\Phi_2(t) + \Phi_1(t) + \Psi_{os}}{2}\right)\cdot\cos(2\pi f_c t) \\ & -2\sin\left(\frac{-\Phi_2(t) + \Phi_1(t) + \Psi_{os}}{2}\right)\cos\left(\frac{\Phi_1(t) + \Psi_{os} + \Phi_2(t)}{2}\right)\cdot\sin(2\pi f_c t). \end{aligned} \tag{A.12}$$

Thereafter it can be shown that Eq (A.12) simplifies to

$$\cos(2\pi f_c t + \Phi_1(t) + \Psi_{os}) - \cos(2\pi f_c t + \Phi_2(t)), \tag{A.13}$$

which is exactly (Eq (A.5)) the signal that was required for transmission.

A.3 DEMODULATOR STRUCTURE

In Fig. A.2, the subsequent positions in the OM-demodulator structure are presented. At 1

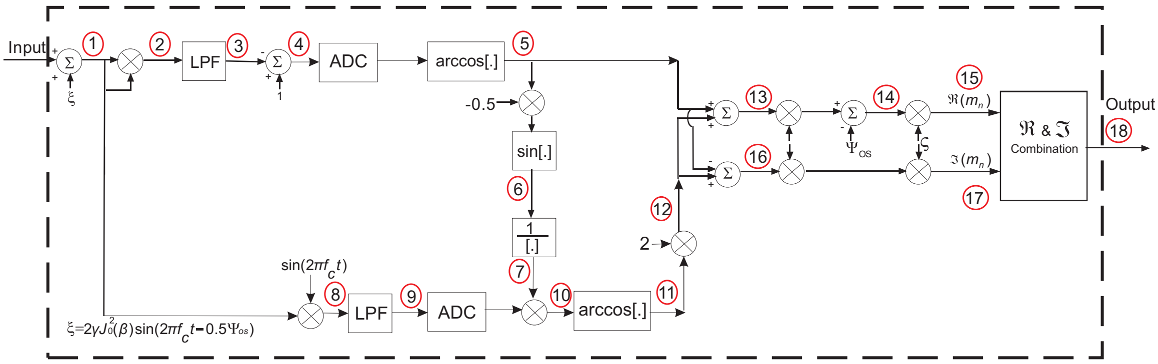

Figure A.2: OM demodulator structure

in Fig. A.2 a received OM-OFDM noise-free signal is given by

$$\cos(2\pi f_c t + \Phi_1(t) + \Psi_{os}) - \cos(2\pi f_c t + \Phi_2(t)). \tag{A.14}$$

Alternatively, Eq (A.14) may also be written as

$$2\sin\left(\frac{\Phi_2(t) - \Phi_1(t) - \Psi_{os}}{2}\right) \cdot \sin\left(2\pi f_c t + \frac{\Phi_1(t) + \Psi_{os} + \Phi_2(t)}{2}\right). \tag{A.15}$$

At 2, the signal can be expressed as

$$\begin{aligned}
&\left(2\sin\left(\frac{\Phi_2(t) - \Phi_1(t) - \Psi_{os}}{2}\right) \cdot \sin\left(2\pi f_c t + \frac{\Phi_1(t) + \Psi_{os} + \Phi_2(t)}{2}\right)\right) \cdot \\
&\left(2\sin\left(\frac{\Phi_2(t) - \Phi_1(t) - \Psi_{os}}{2}\right) \cdot \sin\left(2\pi f_c t + \frac{\Phi_1(t) + \Psi_{os} + \Phi_2(t)}{2}\right)\right) \\
= &\left(2\sin\left(\frac{\Phi_2(t) - \Phi_1(t) - \Psi_{os}}{2}\right) \cdot \sin\left(2\pi f_c t + \frac{\Phi_1(t) + \Psi_{os} + \Phi_2(t)}{2}\right)\right)^2
\end{aligned}$$

$$= 1 - \cos(4\pi f_c t + \Phi_1 + \Psi_{os} + \Phi_2) - \cos(-\Phi_2 + \Phi_1 + \Psi_{os}) + \frac{1}{2}\cos(2\Phi_2 + 4\pi f_c t) + \frac{1}{2}\cos(4\pi f_c t + 2\Phi_1 + 2\Psi_{os}). \quad \text{(A.16)}$$

The low pass filter (LPF), before 3, removes the high-frequency components ($4\pi f_c t$); this results in

$$1 - \cos(-\Phi_2(t) + \Phi_1(t) + \Psi_{os}). \quad \text{(A.17)}$$

A 4th order low pass Butterworth filter proved to be sufficient to remove these high-frequency component signals. In addition, the delay introduced by the Butterworth filter needed to be compensated for. At 4, the signal can be expressed as

$$\cos(-\Phi_2(t) + \Phi_1(t) + \Psi_{os}). \quad \text{(A.18)}$$

The signal at 4 undergoes an analog-to-digital (ADC) conversion. The signal at 5, can be written as

$$-\Phi_{2n} + \Phi_{1n} + \Psi_{os} \quad \text{(A.19)}$$

where Φ_{1n} and Φ_{2n} represent the equivalent discrete real and imaginary OFDM phase mapping. Thereafter at 6, the signal can be expressed as

$$\sin\left(\frac{\Phi_{2n} - \Phi_{1n} - \Psi_{os}}{2}\right). \quad \text{(A.20)}$$

At 7, the signal can be shown to be

$$\frac{1}{\sin\left(\frac{\Phi_{2n} - \Phi_{1n} - \Psi_{os}}{2}\right)}. \quad \text{(A.21)}$$

The signal at 8, can be expressed as

$$(\cos(2\pi f_c t + \Phi_1(t) + \Psi_{os}) - \cos(2\pi f_c t + \Phi_2(t))) \cdot \sin(2\pi f_c t) \quad \text{(A.22)}$$

$$= \frac{1}{2}\sin\left(4\pi f_c t + \Phi_1(t) + \Psi_{os}\right) - \frac{1}{2}\sin\left(\Phi_1(t) + \Psi_{os}\right)$$
$$-\frac{1}{2}\sin\left(4\pi f_c t + \Phi_2(t)\right) + \frac{1}{2}\sin\left(\Phi_2(t)\right). \quad \text{(A.23)}$$

As previously mentioned the LPF removes the high frequency ($4\pi f_c t$) components of the signal. In addition, the delay introduced by the Butterworth filter needed to be compensated for. The signal at 9 is written as

$$-\frac{1}{2}\sin\left(\Phi_1(t) + \Psi_{os}\right) + \frac{1}{2}\sin\left(\Phi_2(t)\right). \quad \text{(A.24)}$$

Applying the following identity [91]

$$\sin(z_1) - \sin(z_2) = 2\cos\left(\frac{z_1 + z_2}{2}\right) \cdot \sin\left(\frac{z_1 - z_2}{2}\right), \quad \text{(A.25)}$$

to Eq (A.24), this results in

$$\cos\left(\frac{\Phi_1(t) + \Phi_2(t) + \Psi_{os}}{2}\right) \cdot \sin\left(\frac{\Phi_2(t) - \Phi_1(t) - \Psi_{os}}{2}\right). \quad \text{(A.26)}$$

The signal at 9 is passed through an ADC. As previously mentioned the signal at 7 is

$$\frac{1}{\sin\left(\frac{\Phi_{2n} - \Phi_{1n} - \Psi_{os}}{2}\right)}. \quad \text{(A.27)}$$

At 10 the signal is written as

$$\frac{\cos\left(\frac{\Phi_{1n} + \Phi_{2n} + \Psi_{os}}{2}\right) \cdot \sin\left(\frac{\Phi_{2n} - \Phi_{1n} - \Psi_{os}}{2}\right)}{\sin\left(\frac{\Phi_{2n} - \Phi_{1n} - \Psi_{os}}{2}\right)} \quad \text{(A.28)}$$
$$= \cos\left(\frac{\Phi_{1n} + \Phi_{2n} + \Psi_{os}}{2}\right).$$

At 11, the signal can be expressed as

$$\frac{\Phi_{1n} + \Psi_{os} + \Phi_{2n}}{2}. \quad \text{(A.29)}$$

At 12, the signal can be written as

$$\Phi_{1n} + \Psi_{os} + \Phi_{2n}. \tag{A.30}$$

At 5 and 12, there are two equations (Eq (A.19) and Eq (A.30)), with two unknowns Φ_1 and Φ_2 (Ψ_{os} is known). To obtain 13, Eq (A.19) and Eq (A.30) (5 and 12) are added, this results in

$$(-\Phi_{2n} + \Phi_{1n} + \Psi_{os}) + (\Phi_{1n} + \Psi_{os} + \Phi_{2n}) = 2\Phi_{1n} + 2\Psi_{os}. \tag{A.31}$$

At 14, the signal can be written as Φ_{1n} and at 15, the real part of the message signal is extracted. In order to extract the imaginary components of the message signal, Eq (A.30) (12) is subtracted from Eq (A.19) (5), this results in 16, which can be shown to be $2\Phi_{2n}$. Thereafter, at 17, the imaginary part of the message signal is extracted. Both the real and imaginary components from 15 and 17 are combined to form the complex received message signal seen at 18.