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Appendices

Appendix A: Proof of Equations (3.20) and (3.31)-(3.33)

A.1 Proof of Equation (3.20)

The average pairwise error probability of (3.19), $P(d)$, can then be written as

$$P(d)=\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\int_{0}^{\infty} exp\left(\frac{-g_{PSK}\left(R_{C_1}d_1+R_{C_2}d_2\right)\gamma_{SD}}{\sin^2\theta}\right)p_{\gamma_{SD}}(\gamma_{SD})\,d\gamma_{SD}\,d\theta$$

$$.\prod_{m=1}^{L}\left(\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\int_{0}^{\infty} exp\left(\frac{-g_{PSK}R_{C_1}d_1\gamma_{SR_m}}{\sin^2\theta_m}\right)p_{\gamma_{SR_m}}(\gamma_{SR_m})\,d\gamma_{SR_m}\,d\theta_m\right)$$

$$+\sum_{L'=1}^{L-1}\sum_{\Omega}\left[\prod_{j\notin\Omega}\left(\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\int_{0}^{\infty} exp\left(\frac{-g_{PSK}R_{C_1}d_1\gamma_{SR_j}}{\sin^2\theta_j}\right)p_{\gamma_{SR_j}}(\gamma_{SR_j})\,d\gamma_{SR_j}\,d\theta_j\right)\right.$$

$$.\prod_{j\in\Omega}\left(1-\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\int_{0}^{\infty} exp\left(\frac{-g_{PSK}R_{C_1}d_1\gamma_{SR_j}}{\sin^2\theta_j}\right)p_{\gamma_{SR_j}}(\gamma_{SR_j})\,d\gamma_{SR_j}\,d\theta_j\right)$$

$$.\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\prod_{j\in\Omega}\int_{0}^{\infty}\int_{0}^{\infty} exp\left(\frac{-g_{PSK}\left(R_{C_1}d_1+\frac{R_{C_2}}{(L'+1)}d_2\right)\gamma_{SD}}{\sin^2\theta}\right)$$

$$\left..\,exp\left(\frac{-g_{PSK}\left(R_{C_1}d_1+R_{C_2}d_2\right)\gamma_{SD}}{\sin^2\theta}\right)p_{\gamma_{SD}}(\gamma_{SD})p_{\gamma_{R_jD}}(\gamma_{R_jD})d\gamma_{SD}\,d\gamma_{R_jD}\,d\theta\right]$$

$$+\prod_{m=1}^{L}\left(1-\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\int_{0}^{\infty} exp\left(\frac{-g_{PSK}R_{C_1}d_1\gamma_{SR_m}}{\sin^2\theta_m}\right)p_{\gamma_{SR_m}}(\gamma_{SR_m})\,d\gamma_{SR_m}\,d\theta_m\right)$$

$$.\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\prod_{m=1}^{L}\int_{0}^{\infty}\int_{0}^{\infty} exp\left(\frac{-g_{PSK}\left(R_{C_1}d_1+\frac{R_{C_2}}{(L'+1)}d_2\right)\gamma_{SD}}{\sin^2\theta}\right)$$

$$.exp\left(\frac{-g_{PSK}\, R_{C_2}d_2\gamma_{R_m D}}{(L+1)\sin^2\theta}\right)p_{\gamma_{SD}}(\gamma_{SD})p_{\gamma_{R_m D}}(\gamma_{R_m D})d\gamma_{SD}\,d\gamma_{R_m D}\,d\theta. \qquad (A.1)$$

Using (3.13), (A.1) can then be written

$$P(d)=\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1+\frac{g_{PSK}\left(R_{C_1}d_1+R_{C_2}d_2\right)\bar{\gamma}_{SD}}{\sin^2\theta}\right)^{-1}d\theta$$

$$.\prod_{m=1}^{L}\left(\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1+\frac{g_{PSK}\,R_{C_1}d_1\bar{\gamma}_{SR_m}}{\sin^2\theta_m}\right)^{-1}d\theta_m\right)$$

$$+\sum_{L'=1}^{L-1}\sum_{\Omega}\left[\prod_{j\notin\Omega}\left(\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1+\frac{g_{PSK}\,R_{C_1}d_1\bar{\gamma}_{SR_j}}{\sin^2\theta_j}\right)^{-1}d\theta_j\right)\right.$$

$$.\prod_{j\in\Omega}\left(1-\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1+\frac{g_{PSK}\,R_{C_1}d_1\bar{\gamma}_{SR_j}}{\sin^2\theta_j}\right)^{-1}d\theta_j\right)\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}$$

$$\left..\left(1+\frac{g_{PSK}\left(R_{C_1}d_1+\frac{R_{C_2}}{(L'+1)}d_2\right)\bar{\gamma}_{SD}}{\sin^2\theta}\right)^{-1}\prod_{j\in\Omega}\left(1+\frac{g_{PSK}\,R_{C_2}d_2\bar{\gamma}_{R_j D}}{(L'+1)\sin^2\theta}\right)^{-1}d\theta\right]$$

$$+\prod_{m=1}^{L}\left(1-\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1+\frac{g_{PSK}\,R_{C_1}d_1\bar{\gamma}_{SR_m}}{\sin^2\theta_m}\right)^{-1}d\theta_m\right)\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}$$

$$.\left(1+\frac{g_{PSK}\left(R_{C_1}d_1+\frac{R_{C_2}}{(L+1)}d_2\right)\bar{\gamma}_{SD}}{\sin^2\theta}\right)^{-1}\prod_{m=1}^{L}\left(1+\frac{g_{PSK}\,R_{C_2}d_2\bar{\gamma}_{R_m D}}{(L+1)\sin^2\theta}\right)^{-1}d\theta, \quad (A.2)$$

where $\bar{\gamma}_{SR_m}=\frac{E_{SR_m}}{N_0}E\left[\left|h_{SR_m}\right|^2\right]$ is the average SNR.

A.2 Proof of Equation (3.31)-(3.33)

From (3.30), I_1, $I_2(j)$, I_3 can be written as

$$I_1 = Pr\{(1+\gamma_{SD})^{\beta}(1+\gamma_{SD})^{(1-\beta)} < 2^{R_c}\}$$
$$= \int_0^{2^{R_c}-1} \frac{1}{\bar{\gamma}_{SD}} exp\left(\frac{-\gamma_{SD}}{\bar{\gamma}_{SD}}\right) d\gamma_{SD} = 1 - exp\left(\frac{(1-2^{R_c})}{\bar{\gamma}_{SD}}\right), \tag{A.3}$$

and

$$I_2(j) = Pr\left\{(1+\gamma_{SD})^{\beta}\left(1+\frac{1}{(L'+1)}\left[\gamma_{SD}+\sum_{j\in\Omega}\gamma_{R_jD}\right]\right)^{(1-\beta)} < 2^{R_c}\right\}$$
$$= \int_0^{A_1'} \frac{1}{\bar{\gamma}_{SD}} exp\left(\frac{-\gamma_{SD}}{\bar{\gamma}_{SD}}\right) d\gamma_{SD}$$
$$\cdot \int_0^{A_2} \cdots \int_0^{A_2} \prod_{j\in\Omega}\left(\frac{1}{\bar{\gamma}_{R_jD}}\right) exp\left(-\sum_{j\in\Omega}\frac{\gamma_{R_jD}}{\bar{\gamma}_{R_jD}}\right)\prod_{j\in\Omega} d\gamma_{R_jD}$$
$$= \left(1 - exp\left(\frac{-A_1'}{\bar{\gamma}_{SD}}\right)\right)\prod_{j\in\Omega}\left(\int_0^{A_2'} \frac{1}{\bar{\gamma}_{R_jD}} exp\left(\frac{-\gamma_{R_jD}}{\bar{\gamma}_{R_jD}}\right) d\gamma_{R_jD}\right)$$
$$= \left(1 - exp\left(\frac{-A_1'}{\bar{\gamma}_{SD}}\right)\right)\prod_{j\in\Omega}\left(1 - exp\left(\frac{-A_2'}{\bar{\gamma}_{R_jD}}\right)\right)$$
$$= \left(1 - exp\left(\frac{(1-2^{R_c})(L'+1)}{\bar{\gamma}_{SD}}\right)\right)\prod_{j\in\Omega}\left(1 - exp\left(\frac{\left(1-2^{\left(\frac{R_c}{1-\beta}\right)}\right)(L'+1)}{\bar{\gamma}_{R_jD}}\right)\right), \tag{A.4}$$

and

$$I_3 = Pr\left\{(1+\gamma_{SD})^{\beta}\left(1+\frac{1}{(L+1)}\left[\gamma_{SD}+\sum_{m=1}^{L}\gamma_{R_mD}\right]\right)^{(1-\beta)} < 2^{R_c}\right\}$$

$$= \int_0^{A_1} \frac{1}{\bar{\gamma}_{SD}} exp\left(\frac{-\gamma_{SD}}{\bar{\gamma}_{SD}}\right) d\gamma_{SD}$$

$$\cdot \int_0^{A_2} \cdots \int_0^{A_2} \prod_{m=1}^{L} \left(\frac{1}{\bar{\gamma}_{R_m D}}\right) exp\left(-\sum_{m=1}^{L} \frac{\gamma_{R_m D}}{\bar{\gamma}_{R_m D}}\right) \prod_{m=1}^{L} \gamma_{R_m D}$$

$$= \left(1 - exp\left(\frac{-A_1}{\bar{\gamma}_{SD}}\right)\right) \prod_{m=1}^{L} \left(\int_0^{A_2} \frac{1}{\bar{\gamma}_{R_m D}} exp\left(\frac{-\gamma_{R_m D}}{\bar{\gamma}_{R_m D}}\right) d\gamma_{R_m D}\right)$$

$$= \left(1 - exp\left(\frac{-A_1}{\bar{\gamma}_{SD}}\right)\right) \prod_{m=1}^{L} \left(1 - exp\left(\frac{-A_2}{\bar{\gamma}_{R_m D}}\right)\right)$$

$$= \left(1 - exp\left(\frac{(1-2^{R_c})(L+1)}{\bar{\gamma}_{SD}}\right)\right) \prod_{m=1}^{L} \left(1 - exp\left(\frac{\left(1-2^{\left(\frac{R_c}{1-\beta}\right)}\right)(L+1)}{\bar{\gamma}_{R_m D}}\right)\right), \quad \text{(A.5)}$$

Appendix B: Proof of Equations (4.38) and (4.40)

B.1 Proof of Equation (4.38)

From (4.37), the CDF of Z, $P_Z(z)$, is given by

$$P_Z(z) = \frac{2^{n_R}}{z\sqrt{\alpha \bar{\gamma}_{SR} \bar{\gamma}_{RD}}} \sum_{i=0}^{n_R-1} \binom{n_R - 1}{i} \frac{(-1)^{n_R-1-i}}{\sqrt{n_R - i}} exp\left(-\left[\frac{(n_R - i)}{\bar{\gamma}_{SR}} + \frac{1}{\alpha \bar{\gamma}_{RD}}\right]\frac{1}{z}\right) K_1\left(\frac{1}{z}\sqrt{\frac{4(n_R - i)}{\alpha \bar{\gamma}_{SR} \bar{\gamma}_{RD}}}\right), \text{(B.1)}$$

Taking the derivative of (B.1) with respect to z and using the expression for the derivative of the modified Bessel function, given in [62] as

$$z\frac{d}{dz}K_v(z) + vK_v(z) = -zK_{v-1}(z). \quad \text{(B.2)}$$

yields (4.38).

B.2 Proof of Equation (4.40)

From (4.39), the PDF of γ_{SRD} is given by

$$p_{\gamma_{SRD}}(\gamma_{SRD}) = \frac{2\gamma_{SRD}\, n_R}{\sqrt{\alpha\bar{\gamma}_{SR}\bar{\gamma}_{RD}}} \sum_{i=0}^{n_R-1} \binom{n_R-1}{i} \frac{(-1)^{n_R-1-i}}{\sqrt{n_R-i}}$$

$$.\,exp\left(-\left[\frac{(n_R-i)}{\bar{\gamma}_{SR}} + \frac{1}{\alpha\bar{\gamma}_{RD}}\right]\gamma_{SRD}\right)\left\{\left[\frac{(n_R-i)}{\bar{\gamma}_{SR}} + \frac{1}{\alpha\bar{\gamma}_{RD}}\right] K_1\left(\gamma_{SRD}\sqrt{\frac{4(n_R-i)}{\alpha\bar{\gamma}_{SR}\bar{\gamma}_{RD}}}\right)\right.$$

$$\left. + \sqrt{\frac{4(n_R-i)}{\alpha\bar{\gamma}_{SR}\bar{\gamma}_{RD}}} K_0\left(\gamma_{SRD}\sqrt{\frac{4(n_R-i)}{\alpha\bar{\gamma}_{SR}\bar{\gamma}_{RD}}}\right)\right\}. \qquad \text{(B.3)}$$

The MGF of γ_{SRD}, $\Psi_{\gamma_{SRD}}(-s)$, can be shown as

$$\Psi_{\gamma_{SRD}}(-s) = \int_0^{\infty} p_{\gamma_{SRD}}(\gamma_{SRD}) exp(-s\gamma_{SRD}) d\gamma_{SRD}$$

$$\Psi_{\gamma_{SRD}}(-s) = \frac{4n_R}{\sqrt{\alpha\bar{\gamma}_{SR}\bar{\gamma}_{RD}}} \sum_{i=0}^{n_R-1} \binom{n_R-1}{i} \frac{(-1)^{n_R-1-i}}{\sqrt{n_R-i}}$$

$$.\left\{\sqrt{\frac{(n_R-i)}{\alpha\bar{\gamma}_{SR}\bar{\gamma}_{RD}}} f_1(s,i) + \frac{1}{2}\left[\frac{(n_R-i)}{\bar{\gamma}_{SR}} + \frac{1}{\alpha\bar{\gamma}_{RD}}\right] f_2(s,i)\right\}, \qquad \text{(B.4)}$$

where

$$f_1(s,i) = \int_0^{\infty} \gamma_{SRD}\, exp\left(-\left[\frac{n_R-i}{\bar{\gamma}_{SR}} + \frac{1}{\alpha\bar{\gamma}_{RD}} + s\right]\gamma_{SRD}\right) K_0\left(\gamma_{SRD}\sqrt{\frac{4(n_R-i)}{\alpha\bar{\gamma}_{SR}\bar{\gamma}_{RD}}}\right) d\gamma_{SRD}$$

and

$$f_2(s,i) = \int_0^{\infty} \gamma_{SRD}\, exp\left(-\left[\frac{n_R-i}{\bar{\gamma}_{SR}} + \frac{1}{\alpha\bar{\gamma}_{RD}} + s\right]\gamma_{SRD}\right) K_1\left(\gamma_{SRD}\sqrt{\frac{4(n_R-i)}{\alpha\bar{\gamma}_{SR}\bar{\gamma}_{RD}}}\right) d\gamma_{SRD}$$

Using [62] we obtain the result in (4.40).

Appendix C: Proof of Equations (5.27) and (5.35)

C.1 Proof of Equation (5.27)

From (5.26), the average pairwise error probability, $P(d)$, is given by

$$P(d)=\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1+\frac{g_{PSK}}{\sin^2\theta}\left(\frac{R_{C_2}d_2\alpha\left(\frac{E_{RD}}{N_0}\right)}{1+\frac{R_{C_2}\left[(1-\alpha)\left(\frac{E_{SD}}{N_0}\right)+\alpha\left(\frac{E_{RD}}{N_0}\right)\right]}{k_p\left(\frac{E_p}{N_0}\right)}}\right)\right)^{-1}$$

$$\cdot\left(1+\frac{g_{PSK}}{\sin^2\theta}\left(\frac{R_{C_1}d_1\left(\frac{E_{SD}}{N_0}\right)}{\left(1+\frac{R_{C_1}\left(\frac{E_{SD}}{N_0}\right)}{k_p\left(\frac{E_p}{N_0}\right)}\right)}+\frac{R_{C_2}d_2(1-\alpha)\left(\frac{E_{SD}}{N_0}\right)}{1+\frac{R_{C_2}\left[(1-\alpha)\left(\frac{E_{SD}}{N_0}\right)+\alpha\left(\frac{E_{RD}}{N_0}\right)\right]}{k_p\left(\frac{E_p}{N_0}\right)}}\right)\right)^{-1}d\theta. \quad \text{(C.1)}$$

From (C.1), the average pairwise error probability can be shown as

$$P(d)=\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1+\frac{A(d)}{\sin^2\theta}\right)^{-1}\left(1+\frac{B(d)}{\sin^2\theta}\right)^{-1}d\theta$$

$$=\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(\frac{\sin^2\theta}{\sin^2\theta+A(d)}\right)\left(\frac{\sin^2\theta}{\sin^2\theta+B(d)}\right)d\theta$$

$$=\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1-\frac{A(d)}{\sin^2\theta+A(d)}\right)\left(1-\frac{B(d)}{\sin^2\theta+B(d)}\right)d\theta$$

$$P(d)=\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1-\frac{A(d)}{\sin^2\theta+A(d)}-\frac{B(d)}{\sin^2\theta+B(d)}+\frac{A(d)B(d)}{(\sin^2\theta+A(d))(\sin^2\theta+B(d))}\right)d\theta, \quad \text{(C.2)}$$

Applying a partial fraction expansion into the last term of (C.2), the average pairwise error probability, $P(d)$, is given by

$$P(d)=\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1-\frac{A(d)}{\left(\sin^{2}\theta+A(d)\right)}-\frac{B(d)}{\left(\sin^{2}\theta+B(d)\right)}+\frac{B(d)}{\left(B(d)-A(d)\right)}\frac{A(d)}{\left(\sin^{2}\theta+A(d)\right)}\right.$$

$$\left.+\frac{A(d)}{\left(A(d)-B(d)\right)}\frac{B(d)}{\left(\sin^{2}\theta+B(d)\right)}\right)d\theta$$

$$=\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1+\frac{A(d)}{\left(B(d)-A(d)\right)}\frac{A(d)}{\left(\sin^{2}\theta+A(d)\right)}+\frac{B(d)}{\left(A(d)-B(d)\right)}\frac{B(d)}{\left(\sin^{2}\theta+B(d)\right)}\right)d\theta. \quad \text{(C.3)}$$

Using [62] we obtain the result in (5.27).

C.2 Proof of Equation (5.35)

From (5.34), the average pairwise error probability is given by

$$P(d)=\left(\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1+\frac{C(d)}{\sin^{2}\theta_1}\right)^{-1}d\theta_1\right)\left(\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1+\frac{D(d)}{\sin^{2}\theta_2}\right)^{-1}d\theta_2\right)$$

$$+\left(1-\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1+\frac{D(d)}{\sin^{2}\theta_1}\right)^{-1}d\theta_1\right)$$

$$\cdot\left(\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1+\frac{A(d)}{\sin^{2}\theta_2}\right)^{-1}\left(1+\frac{B(d)}{\sin^{2}\theta_2}\right)^{-1}d\theta_2\right), \quad \text{(C.4)}$$

The average pairwise error probability, P (d), can be written as

$$P(d)=\left(\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1-\frac{C(d)}{\sin^{2}\theta_1+C(d)}\right)d\theta_1\right)$$

$$\cdot\left(\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1-\frac{D(d)}{\sin^{2}\theta_2+D(d)}\right)d\theta_2\right)$$

$$+\left(1-\frac{1}{\pi}\int_{0}^{\frac{(M-1)\pi}{M}}\left(1-\frac{D(d)}{\sin^2\theta_1+D(d)}\right)d\theta_1\right)$$

$$\cdot\left(\frac{1}{\pi}\int_0^{\frac{(M-1)\pi}{M}}\left(1-\frac{A(d)}{\left(\sin^2\theta_2+A(d)\right)}\right)\left(1-\frac{B(d)}{\left(\sin^2\theta_2+B(d)\right)}\right)d\theta_2\right). \quad \text{(C.5)}$$

Applying a partial fraction expansion into the last term of (C.5) and using [62] we obtain the result in (5.35).

Introduction

Whenever size, power, or other constraints preclude the use of multiple-input multiple-output (MIMO) systems, wireless systems cannot benefit from the well-known advantages of space-time coding (STC) methods. Also the complexity (multiple radio-frequency (RF) front ends at both the transmitter and the receiver), channel estimation, and spatial correlation in centralized MIMO systems degrade the performance. In situations like these, the alternative would be to resort to cooperative communications via multiple relay nodes. When these nodes work cooperatively, they form a virtual MIMO system. The destination receives multiple versions of the same message from the source and one or more relays, and combines these to create diversity.

Assistance professor Mohamed Mustafa Mohamed Elfituri is the dean of the College of Electrical and Electronics Technology, Benghazi, Libya since 2011. He received his Ph.D. in Department of Electrical and Computer Engineering, University of Concordia University, Montreal, Canada in May 2009, and his M.Sc. in Department of Electrical and Electronics Engineering, University of Garyounis, Benghazi, Libya in Feb. 1999, and his B.Sc. in Department of Electrical and Electronics Engineering, University of Garyounis, Benghazi, Libya in July 1993. Dr. Mohamed is a lecturer in Department of Electrical and Electronics Engineering, University of Garyounis, Benghazi, Libya from 1999 to 2003; and he has been an assistance professor since 2012. In addition to teaching, Dr. Mohamed worked as RF Designer from 2009 to 2010 at Barrett Broadband Networks Inc., Woodstock, NB, Canada.

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