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• **Supplementary File** •

Joint frequency-phase estimation for pilot-limited communication systems: A novel method based on length-variable auto-correlation operator

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Appendix A Numerical results and analysis

In this section, we will evaluate the performance of the proposed NFPE method along with the introduced TFPE method. We will also assess the effect of the existing frequency offset on the performance of both methods. Besides, we will discuss the impact of the variable correlation length in (6) on the performance of the proposed NFPE method. Monte-Carlo simulations are used to analyze the mean square error (MSE) and bit error rate (BER) of both the methods.

The QPSK modulation is applied, the symbol duration $T_s = 1$ and the phase offset $\theta = 2\pi/3$ are assumed without loss of generality, the pilot length is limited to 9 or 15 symbols i.e. $L = 9, 15$, which can satisfy the pilot-limited communication systems with short data packet transmission. Moreover, the variable correlation length L' in (6) is chosen from the sets $\{6, 7, 8, 9\}$ for $L = 9$ and $\{9, 11, 13, 15\}$ for $L = 15$. Other parameters shown in the TFPE and NFPE methods are listed in Table I and Table II, where (3), (4) and (8) are considered for the TFPE method, (6), (7) and (9) are also considered for the NFPE method.

Figure B1 and Figure B2 show the evaluation of the NFPE and TFPE methods versus different frequency offsets within the corresponding threshold frequencies for $L = 9$ and $L = 15$, respectively. As shown in the two figures, when the existing frequency offsets are equal to or close to any one of the thresholds of the frequency or phase offset estimation, the MSE performance of both the two methods is not good, but where the proposed NFPE method can provide a better performance compared with the TFPE method especially for small pilot overhead. Conversely, when the existing frequency offsets are less than the defined thresholds, the performance of both the two methods is good, where the TFPE method can achieve slightly better performance than the proposed NFPE method without frequency estimation (FE). Obviously, the performance of the TFPE method without the FE will deteriorate sharply. The above results accord with BER performance of both methods as shown in Figure B3.

Figure B4 and Figure B5 depict the evaluation of the NFPE and TFPE methods versus large frequency offset within the corresponding threshold frequencies and different variable correlation lengths for $L = 9$ and $L = 15$, respectively. In the two experiments, since the existing frequency offset are larger than the defined threshold for the phase estimation in the NFPE method, the frequency estimation needs to be pre-considered, the same as that in the TFPE method. As shown, for the proposed NFPE method, when the variable correlation lengths $\{L'\}$ are more than the correlation delay lengths $\{\alpha'\}$ but less than the assumed pilot lengths $\{L\}$, some performance loss will occur, which is significantly improved with an increase of the pilot length. Moreover, the performance of the NFPE method is better than that of the TFPE method, which means that the proposed NFPE method can be more suitable for high-order modulation systems. This is because high-order modulation systems are more sensitive to the residual phase offset. However, the proposed NFPE method has smaller residual phase offsets than the TFPE method according to our simulation results.

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Table A1 Specific parameters for $L = 9$

Methods		Parameters	
TFPE	CORR I	$\alpha = 5$ for good performance	$\alpha = 1$ for wide range
	FE	$\lvert f_d \rvert < \lvert f_{d,threshold} \rvert = 0.1$	$\lvert f_d \rvert < \lvert f_{d,threshold} \rvert = 0.5$
	PE I	$\lvert \Delta f_d \rvert \approx 0$ required	$\lvert \Delta f_d \rvert \approx 0$ required
NFPE	CORR II	$\alpha = 5$ for good performance	$\alpha = 1$ for wide range
	FE	not needed	$\lvert f_d \rvert < \lvert f_{d,threshold} \rvert = 0.5$
	PE II	$\alpha' = \alpha$ $\lvert f_d \rvert < \lvert f'_{d,threshold} \rvert = 0.1$	$\alpha' = 5$ $\lvert f_d \rvert < \lvert f'_{d,threshold} \rvert = 0.1$

Table A2 Specific parameters for $L = 15$

Methods		Parameters	
TFPE	CORR I	$\alpha = 8$ for good performance	$\alpha = 1$ for wide range
	FE	$\lvert f_d \rvert < \lvert f_{d,threshold} \rvert \approx 0.06$	$\lvert f_d \rvert < \lvert f_{d,threshold} \rvert = 0.5$
	PE I	$\lvert \Delta f_d \rvert \approx 0$ required	$\lvert \Delta f_d \rvert \approx 0$ required
NFPE	CORR II	$\alpha = 8$ for good performance	$\alpha = 1$ for wide range
	FE	not needed	$\lvert f_d \rvert < \lvert f_{d,threshold} \rvert = 0.5$
	PE II	$\alpha' = \alpha$ $\lvert f_d \rvert < \lvert f'_{d,threshold} \rvert \approx 0.06$	$\alpha' = 8$ $\lvert \Delta f_d \rvert < \lvert f'_{d,threshold} \rvert \approx 0.06$

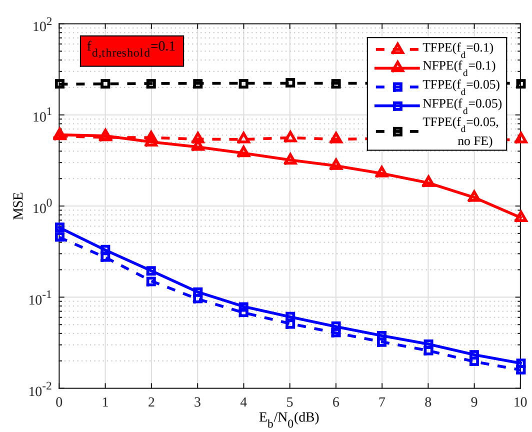

Figure A1 Evaluation of NFPE and TFPE for $L = 9$ versus different frequency offsets.

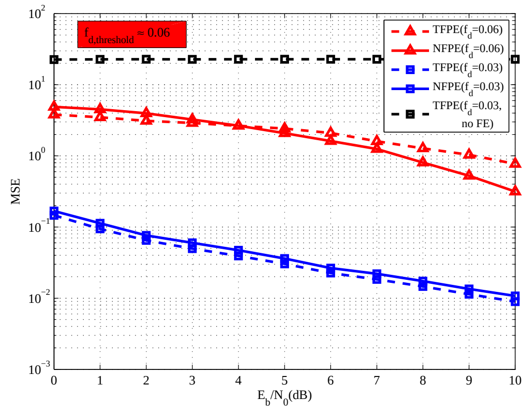

Figure A2 Evaluation of NFPE and TFPE for $L = 15$ versus different frequency offsets.

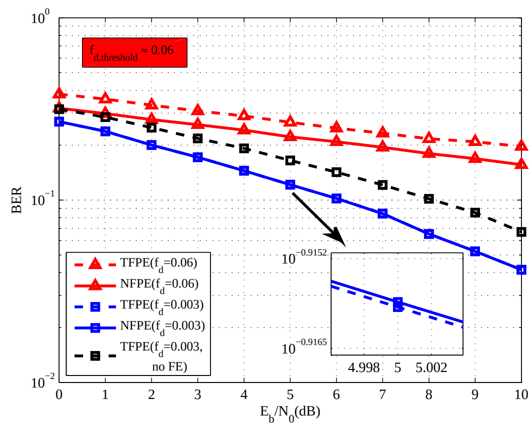

Figure A3 Evaluation of NFPE and TFPE for $L = 15$ and a short data packet with $M = 256$.

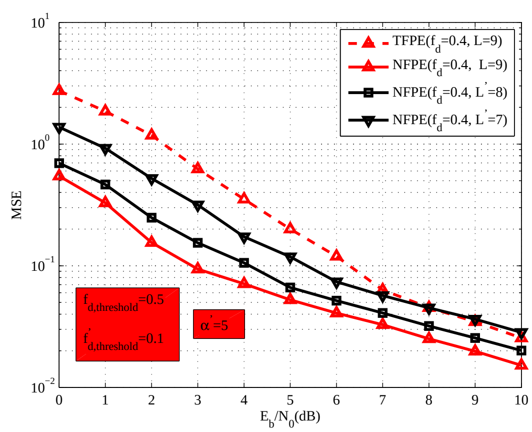

Figure A4 Evaluation of NFPE and TFPE for $L = 9$ versus large frequency offset and different variable correlation lengths.

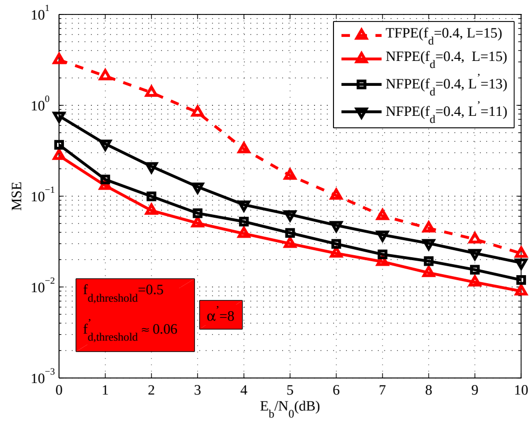

Figure A5 Evaluation of NFPE and TFPE for $L = 15$ versus large frequency offset and different variable correlation lengths.

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