Fig. 1.(a) Fundamental mixer (modulation frequency: $f_c = 1/T_c$), (b) time-interleaved (TI) mixer array with a time-interleaving factor of *M* (modulation frequency: f_c/M), and (c) rectangular pulse trains for the fundamental mixer and the TI mixer arrays.

Fig. 2. Fundamental and time-interleaved carrier modulations with bipolar differential carriers: (a) modulation with fundamental carrier frequency using bipolar *on-off* switches (①:input signal; ②: bipolar rectangular carrier pulse; ③: modulated output; and ④: spectral components of the output normalized by the input peak magnitude), (b) time-interleaved modulation with $⅓ f_c$ of carrier frequency (time interleaving factor: 3, ①: input signal; ②, ③ and ④: bipolar rectangular *subcarrier* pulses; ⑤, ⑥ and ⑦: modulated outputs by ②, ③ and ④, respectively; ⑧: final time-interleaved output; and ⑨: spectral components of the output normalized by the input peak magnitude). For both cases, ⓐ$= f_c \pm f_s$, ⓑ$= 3f_c \pm f_s$, ⓒ$= 5f_c \pm f_s$, and ⓓ$= 7f_c \pm f_s$.

Fig. 3. A transversal filter equivalent to the delay-sum operation in the time-interleaved carrier signal in (3): $w_0 = w_1 = w_2 = w_3 = w_{M-1} = 1$.

Fig. 4. Rectangular pulse subcarriers (①: a unipolar subcarrier, ②: a nonsymmetrical bipolar subcarrier, and ③: an asymmetric bipolar subcarrier)

Fig. 5. Time-interleaved carrier modulation with interleaving factor *M*=2: (a) 25% duty-cycle, (b) 75% duty-cycle.

Fig. 6. (a) Single-balanced switching mixer (ⓐ and ⓑ: square-waves turning switch $M_{s1,2}$ *on* and *off* alternatively, ①: transconductor output signal and noise currents, ②: bipolar square-wave equivalent to the switch *on-off* modulation, and ③: demodulated signal and noise outputs), (b) conceptual description of the signal and noise demodulation in one-sided spectral domain (①: input signal current to the demodulator, ②: spectral tones of the bipolar square-wave, and ③: demodulated signal and noise outputs).

Fig. 7. Rectangular carrier pulses with a duty cycle $\Delta T/T_c \leq 50\%$ (T_c: period, ①: $\Psi_{ⓐ}(t)$- unipolar pulse, ②: $\Psi_{ⓑ}(t)$- nonsymmetrical bipolar pulse, ③: $\Psi_{ⓒ}(t)$ - asymmetric bipolar differential ($T_d = 1/2T_c$) pulse, and ④: $\Psi_{ⓓ}(t)$ - asymmetric bipolar pulse with an arbitrary T_d under a constraint of $\Delta T \leq T_d \leq T_c - \Delta T$.

Fig. 8. Noise figure NF(*m*=1) when the fundamental tone of each carrier in Fig. 7 is utilized for the carrier demodulation: (a) NF(*m*=1) with the carrier $\Psi_{ⓐ}(t)$, (b) NF(*m*=1) with the carrier $\Psi_{ⓑ}(t)$, (c) NF(*m*=1) with the carrier $\Psi_{ⓒ}(t)$ and (d) NF(*m*=1) with the carrier $\Psi_{ⓓ}(t)$ ($\Delta T/T_c$ =37%) . Theoretical calculations are based on the expressions of $G_{ps,m}$ and G_{pn} in TABLE I. Simulations are done based on a behavioral mixer model in ADS.

Fig. 9. Time-interleaved carrier modulation/demodulation with a time interleaving factor of *M*: (a) time-interleaved mixer array with uncorrelated noises to each mixer (UNTI-mixer array), (b) time-interleaved mixer array with correlated noises to each mixer (CNTI-mixer array).

Fig. 10. Filtering rectangular carrier pulses using a transversal filter which is equivalent to the carrier synthesis based on the delay-sum operation in time-interleaved mixer arrays with *M* of time interleaving factor. ①: $\Psi_{s,①}(t)$- unipolar subcarrier pulse, ②: $\Psi_{s,②}(t)$- nonsymmetrical bipolar subcarrier pulse, ③: $\Psi_{s,③}(t)$ - asymmetric bipolar differential (T_{dx}= ½MT_c) subcarrier pulse, and ④: $\Psi_{s,④}(t)$ - asymmetric bipolar subcarrier pulse with an arbitrary T_{dx} under a constraint of $\Delta T_x \leq T_{dx} \leq MT_c - \Delta T_x$.

Fig. 11. Signal power gain, correlated noise power gain, and uncorrelated noise power gain for a 3-mixer array (*M*=3) with various types of subcarriers described in Fig. 10: (a) case with the unipolar subcarrier $\Psi_{s,①}(t)$, (b) case with the nonsymmetrical bipolar subcarrier $\Psi_{s,②}(t)$, (c) case with the asymmetric differential bipolar subcarrier $\Psi_{s,③}(t)$, and (d) case with the asymmetric bipolar subcarrier $\Psi_{s,④}(t)$ with an arbitrary delay of T_{dx}. Theoretical calculations are based on the expressions of $G_{ps,m}$ and $G_{pn,u}$ in TABLE II. Simulations are done based on a behavioral mixer model in ADS.

Fig. 12. Noise filtering in time-interleaved carrier modulations and demodulations: (a) time-interleaved demodulator array with filtering uncorrelated noises, (b) time-interleaved demodulator array with filtering correlated noises.

Fig. 13. (a) Noise filtering around fundamental frequency of the *subcarrier* $\Psi_{ic}(t)$ with a highpass filter in time-interleaved mixer array with a time interleaving factor *M*=3, (b) conceptual description of spectral tones in the single path of the array.

Fig. 14. Signal power gain and uncorrelated noise power gain after a highpass noise filtering for 3-mixer array (*M*=3) with various types of subcarriers described in Fig. 10: (a) case with the unipolar subcarrier $\Psi_{s,①}(t)$, (b) case with the nonsymmetrical bipolar subcarrier $\Psi_{s,②}(t)$, (c) case with the asymmetric differential bipolar subcarrier $\Psi_{s,③}(t)$, and (d) case with the asymmetric bipolar subcarrier $\Psi_{s,④}(t)$ with an arbitrary delay of T_{dx}. Theoretical calculations are based on the expressions of $G_{ps,m}$ and $G_{pn,u}$ in TABLE III. Simulations are done based on a behavioral mixer model in ADS

Fig. 15. Time-interleaving process with errors from gain and delay mismatches among the array elements (the dotted rectangular pulses are ideal subcarriers). $\Delta T_{\varepsilon,n}$ (*n*=1 to M-1) represents delay mismatch in each subcarrier with reference to the subcarrier of ①. $\Delta w_{\varepsilon,n}$ (*n*=1 to M-1) expresses gain mismatch from in each array path with reference to the path modulated by the subcarrier of ①.

Fig. 16. Time-interleaving process with errors from gain and delay mismatches among the array elements (the dotted rectangular pulses are ideal subcarriers). $\Delta T_{\varepsilon,n}$ (n=1 to M-1) represents delay mismatch in each subcarrier with reference to the subcarrier of ①. $\Delta w_{\varepsilon,n}$ (n=1 to M-1) expresses gain mismatch from in each array path with reference to the path modulated by the subcarrier of ①.

Fig. 17. Contour plots of the noise factor, F(m=3) in (13), of UNTI-mixer arrays with M=3 (duty-cycle: 50%) under weight and delay mismatches: (a) noise factor without noise filtering, (b) noise factor with an ideal bandpass noise filtering, and (c) noise factor with an ideal high-pass noise filtering (only fundamental tone, $f_c/3$, is rejected by an ideal HPF).

TABLE I. SIGNAL POWER GAIN ($G_{PS,M}$) AND NOISE POWER GAIN (G_{PN}) IN THE DEMODULATION PROCESS BY EACH CARRIER IN FIG. 7.

TABLE II. SIGNAL POWER GAIN ($G_{PS,M}$) AND NOISE POWER GAIN (G_{PN}) IN THE TIME-INTERLEAVED DEMODULATION PROCESS PERFORMED BY EACH CARRIER IN FIG. 10.

TABLE III. SIGNAL POWER GAIN ($G_{PS,M}$) AND NOISE POWER GAIN ($G_{PN,U}$) AFTER HIGH-PASS NOISE FILTERING IN THE TIME-INTERLEAVED DEMODULATION PROCESS PERFORMED BY EACH CARRIER IN FIG. 10.