Antenna Downselection for Co-Channel Interference Mitigation in a Mobile-to-Mobile Channel

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***Abstract* — The performance of multi-antenna receivers in co-channel interference is investigated for narrow-band links in non-line-of-sight (NLOS) and line-of-sight (LOS) mobile-to-mobile channels. A novel architecture utilizing antenna down-selection is analyzed in simulation and compared with the performance of a conventional array architecture. Various down-selection criteria are proposed and analyzed. The simulation results show excellent performance enhancement for an MMSE selection algorithm. Several other methods are also analyzed and compared with promising results using the simple method of maximum power selection. Results are compared in terms of estimated complementary cumulative distribution functions of output signal-to-interference-plus-noise ratio (SINR) derived from Monte Carlo simulations.**

***Index Terms*—Wireless communications, adaptive array, antenna down-selection, co-channel interference, mobile-to-mobile channel.**

I. Introduction

The study of transmit and receive antenna selection has received a great deal of attention in the scientific literature. Many of the published papers consider selection for improving MIMO system capacity [1-6] and some look at interference mitigation for simple fading models [7-8]. This study considers receive antenna selection in an interference-limited mobile-to-mobile environment.

The mobile-to-mobile environment is expected to become more important with the advent of ad-hoc and mesh networks. It is different from the cellular environment in several ways such as the assumption of local scattering at both nodes and a spectrum that no longer follows the Jakes model [9,12]. An extensive set of mobile-to-mobile measurements shows distinct differences in the received spectra of mobile-to-mobile versus static environments [16]. It is believed that "interference in wireless systems is one of the most significant factors that limit the network capacity and scalability of wireless mesh networks" [17]. The current study seeks to help address this problem.

This study is partly based on the work done in [10], which develops a model for the co-channel interference problem and analyzes the output SINR for various antenna array configurations. The study in [11] extended this to consider various downselection criteria. This paper further extends these criteria and develops a time-domain model to allow for realistic parameter estimation. The analysis is also extended to include line-of-sight (LOS) environments.

II. Array Architecture

The proposed antenna array is composed of N sectored antennas with non-overlapping beams covering the entire azimuth plane. The outputs of these N antennas are fed to a switch, which selects K of the antennas to be used for processing. A previous study showed this architecture yielded a substantial improvement in array performance over a standard K-element system using optimal combining [11]. Increases in system complexity over the conventional system come from N-K additional antennas, switching circuitry, and signal processing to determine which antenna elements to choose in a given scenario. Both architectures use K "RF chains". The architecture of the K-element system (for K=2) is shown in Figure 1 (left). The other diagram in the figure illustrates the N-select-K architecture described in this section where N=4 and K=2.

The simulation of this system employs the two-ring channel model described in [9], which is used to characterize narrowband channels in non-line-of-sight (NLOS) environments. The model was extended to include a LOS component, discussed in Section III.

III. Signal Model and Processing

Akki & Haber proposed a time-domain fading model [12] for mobile-to-mobile wireless communication. This model, adapted for the purposes of this study, is given by

Prepared through collaborative participation in the Communications and Networks Consortium sponsored by the U. S. Army Research Laboratory under the Collaborative Technology Alliance Program, Cooperative Agreement DAAD19-01-2-0011.

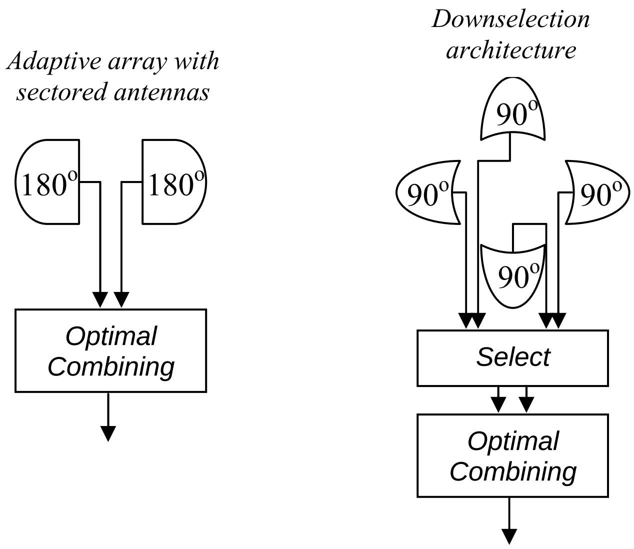

Figure 1. Multi-Antenna Architectures using sectored antennas showing varying degrees of coverage

$$h_{nm}(t) = \sum_{l=1}^{L+1} A_{lm}\Omega_n(\theta_{lm}) e^{j(\omega_{lm}t+\phi_{lm})} \qquad (1)$$

where l=1 corresponds to the LOS component and l=2,…,L+1 to the L NLOS multipath components, A_{lm} is the amplitude associated with the l^{th} multipath component of the m^{th} signal, Ω_n is the n^{th} receive antenna pattern function, θ_{lm} is the position angle of the lm scatterer on the scattering ring around the receiver, φ_{lm} is a random phase uniformly distributed over $(-\pi,\pi]$, and ω_{lm} is the Doppler shift given by

$$\omega_{lm} = \omega_{RX}\cos(\theta_{lm}) + \omega_{TX}\cos(\xi_{lm}) \qquad (2)$$

where ω_{RX} and ω_{TX} are the maximum Doppler shifts associated with the RX and TX velocities respectively, and ξ_{lm} is the angular position of the lm scatterer on the scattering ring around the m^{th} transmitter.

The amplitudes are fixed to yield average desired and interference signal powers of 1. Incorporating the Ricean K-factor (K_R) to account for LOS channels, the amplitudes of the desired signal are given by

$$A_{11} = \sqrt{\frac{K_R}{K_R+1}} \qquad (3)$$

for the LOS component and

$$A_{l1} = \sqrt{\frac{1}{L(K_R+1)}} \quad \text{for } l = 2, \ldots, \text{L+1} \qquad (4)$$

for the L NLOS components. The amplitudes of the signals from the M-1 interference sources (m = 2, …, M) are given by

$$A_{lm} = \frac{A_{l1}}{\sqrt{M-1}} \qquad (5)$$

The received signal at the n^{th} antenna is given by

$$x_n(t) = \sum_{m=1}^{M} h_{nm}(t) a_m(t) + \nu_n(t)$$
$$= \sum_{m=1}^{M}\sum_{l=1}^{L+1} A_{lm}\Omega_n(\theta_{lm}) e^{j(\omega_{lm}t+\phi_{lm})} a_m(t) + \nu_n(t) \qquad (6)$$

where $a_m(t)$ is the m^{th} transmitted signal ($a_1(t)$ is the desired signal) and $\nu_n(t)$ is the noise at the n^{th} antenna. For the transmitted signals, we have assumed the desired signal to be QPSK and the interferers to be white Gaussian noise processes.

To process the received signals, we apply a weight vector $\vec{w}$ to the data:

$$y(t) = \vec{w}^H \vec{x}(t), \qquad (7)$$

where $\vec{x}(t)$ is the column vector given by stacking the K selected antenna outputs and $\vec{w}$ is given by

$$\vec{w} = \hat{R}_{xx}^{-1}\hat{r}_{xd} \qquad (8)$$

The autocorrelation and cross-correlation estimates are computed by averaging over a training period of length T_c.

$$\hat{r}_{xd} = \frac{T_s}{T_c}\sum_{p=0}^{\frac{Tc}{Ts}-1} \vec{x}(pT_s) a_1^*(pT_s) \text{ and} \qquad (9)$$

$$\hat{R}_{xx} = \frac{T_s}{T_c}\sum_{p=0}^{\frac{Tc}{Ts}-1} \vec{x}(pT_s)\vec{x}^H(pT_s) \qquad (10)$$

Here, p represents the training symbol index and T_s is the symbol period. The estimates (9-10) are used to compute the weights, which are applied to the data sequence. For these simulations, we have assumed T_s = 0.2μs and T_c = 25μs.

For each Monte Carlo iteration, SINR values using optimal combining for all possible combinations of N-choose-K antennas are computed and the downselection criteria are used to select the appropriate result.

IV. Downselection Criteria

The mean-square error (MSE) of the processed signal is given by

$$E\left\{(\vec{w}^H\vec{x} - a_1)(\vec{w}^H\vec{x} - a_1)^H\right\}$$
$$= (\vec{w}^H - r_{xd}^H R_{xx}^{-1}) R_{xx} (\vec{w}^H - r_{xd}^H R_{xx}^{-1})^H + 1 - r_{xd}^H R_{xx}^{-1} r_{xd} \qquad (11)$$
$$\approx 1 - r_{xd}^H R_{xx}^{-1} r_{xd}$$

The above approximation is valid assuming the estimates $\hat{R}_{xx}$ and $\hat{r}_{xd}$ are fairly accurate.

MMSE Downselection

By computing the weight vector $\vec{w}$, the receiver has all the information necessary to estimate the MSE. The proposed MMSE algorithm for selecting antennas on which to perform optimal combining is to compute

$$\hat{r}_{xd}^H \hat{R}_{xx}^{-1}\hat{r}_{xd} = \hat{r}_{xd}^H \vec{w} \qquad (12)$$

for all N-choose-K combinations and select the combination that maximizes the expression, thereby minimizing the MSE.

Incremental Antenna Selection

A suboptimal approach requiring less computation can be derived by choosing one antenna that maximizes the expression (12), then choosing a second antenna based on the same criterion, then a third, and so on until all K antennas have been chosen [13]. This method requires $NK - \binom{K}{2}$ computations compared to $\binom{N}{K}$ for the MMSE method. Here, the operator $\binom{A}{B}$ indicates the number of unordered subsets of size B that can be obtained from the set {1,2,…,A}. This is often referred to as A-choose-B.

Using this method, the first antenna chosen will be the one with the largest estimated input SINR. To illustrate this, consider the expression (11) where all of the terms are scalars since only one antenna is involved. By using (6), it is easy to show that

$$r_{xd,n} = E\{x_n(t)a_1^*(t)\} = h_{n1}(t) \text{ and} \tag{13}$$

$$R_{xx,n} = E\{x_n(t)x_n^H(t)\} = \sum_{m=1}^{M} |h_{nm}(t)|^2 + \sigma_n^2 = P_{d,n} + P_{I,n} + \sigma_n^2 \tag{14}$$

where $P_{d,n}$, $P_{I,n}$, and σ_n^2 are the desired signal, interference, and noise powers at the n^th antenna respectively.

The expression (*) then becomes

$$1 - r_{xd,n}^H R_{xx,n}^{-1} r_{xd,n} = 1 - \frac{|r_{xd,n}|^2}{R_{xx,n}} = \frac{R_{xx,n} - |r_{xd,n}|^2}{R_{xx,n}}$$
$$= \frac{P_{d,n} + P_{I,n} + \sigma_n^2 - P_{d,n}}{P_{d,n} + P_{I,n} + \sigma_n^2} = \frac{1}{SINR_n + 1} \tag{15}$$

Minimizing (15) over all n is equivalent to maximizing ($SINR_n$+1), which is equivalent to maximizing $SINR_n$. By using estimates of the autocorrelation and cross-correlation functions, the algorithm will select the antenna with the highest estimated input SINR. Choosing subsequent antennas involves more complicated expressions, but each can be implemented by simply using (12).

Ad-hoc Downselection Methods

Three other selection algorithms will be considered:

1. Select the two antennas with the largest total power
2. Select the two antennas with the largest signal power
3. Select the two antennas with the largest SINR

Bounds and Baseline

The simulation results of the five selection algorithms above will be compared with:

1. the maximum output SINR over all N-choose-K combinations (upper bound)
2. the minimum output SINR over all N-choose-K combinations (lower bound)
3. the performance of optimal combining on a K-element sectored system (baseline)
4. the performance of a random selection of K antennas to compare with the baseline

V. RESULTS

Two antenna configurations were simulated while varying the speed of the mobile nodes, the number of interference sources, and the Ricean K-factor. For simplicity, a four-antenna solution was simulated followed by a nine-antenna configuration to illustrate additional gains that can be derived through higher-order antenna diversity. All of the simulations assume L=10 scatterers per source and average receive SNR and INR of 40dB.

Four antenna architecture; two element processing

Figure 2 shows the estimated output SINR distributions for the various downselection criteria for a 4-select-2 architecture in a static NLOS environment. All of the results presented in this paper are derived from 1,000 Monte Carlo simulations.

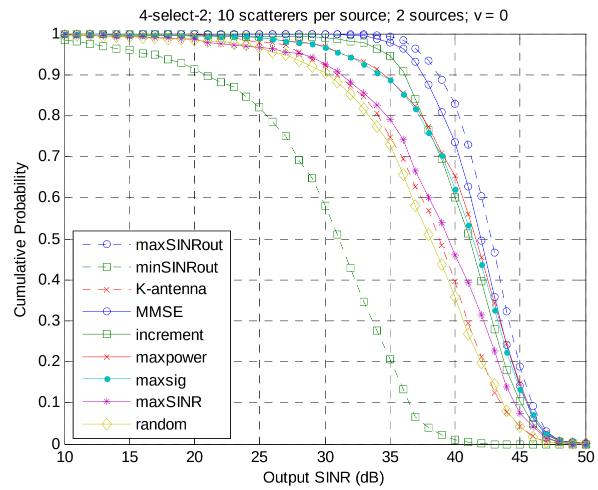

Figure 2. CCDF estimates of output SINR for 4-select-2 architecture, 0 m/s, with 1 interference source, and NLOS conditions.

The output SINR using optimal combining is computed for all N-choose-K antenna combinations. The K-element subset of antennas that yields the maximum output SINR out of all possible subsets is found and results are shown as the curve labeled "maxSINRout", representing the upper bound on system performance. The result of always choosing the antenna pair with the minimum output SINR is shown as the curve labeled "minSINRout", and the baseline case of a K-element array as "K-antenna" (here K=2). The MMSE selection described in Section IV is labeled "MMSE", the incremental selection as "increment", the maximum power criterion as "maxpower", the maximum signal power criterion as "maxsig", the maximum SINR criterion as "maxSINR", and the random antenna selection as "random".

Notice that the MMSE selection scheme does not achieve the upper bound. When the exact channel state information (CSI) is available, the bound is achieved, but in this case, the CSI is estimated by averaging, so the effects of noise and co-channel interference degrade the auto- and cross-correlation estimates and corrupt the MMSE selection criterion. The MMSE algorithm is the best choice for this scenario and is not difficult to compute based on the assumption of a training period. The incremental approach is close to the performance of the max power and max signal power criteria, but performs slightly better.

Now consider the case where the desired signal has a Ricean K-factor of 20dB and the interference is NLOS. Results of this scenario are illustrated in Figure 3.

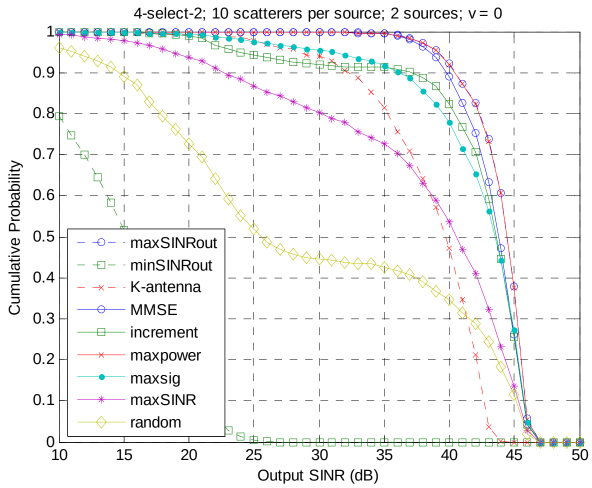

Figure 3. CCDF estimates of output SINR for 4-select-2 architecture, 0 m/s, with 1 interference source, and LOS conditions for the desired signal.

In this case, the maximum power criterion performs the best and is also the simplest to implement. The other algorithms suffer relative to the NLOS case except for the MMSE selection algorithm. It is also interesting to note that the random antenna selection performs much worse in this case than the baseline K-element architecture. In general, the average SINR of the two algorithms are almost identical unless the desired signal has a LOS component. When that happens, the random algorithm will often choose sectors that do not contain the LOS component, which severely reduces the SNR. The K-element architecture will always contain the LOS component and does not suffer in this way.

Consider the average output SINR for each of the algorithms as a function of the K-factor of the desired signal. This result is shown in Figure 4 for K-factors from 0 (NLOS) to 20 (13dB). The values on the left side of Figure 4 (where K = 0) correspond to the average of the distributions shown in Figure 2 and the values on the right are almost identical to the averages of the curves shown in Figure 3. Somewhere near K = 2 (3dB), the maximum power algorithm surpasses the performance of the MMSE algorithm. In measured data, much larger K-factors around 10-20dB were found to be common [14-15], so in a scenario where the desired signal is expected to have a LOS component, the maximum power algorithm will likely perform the best.

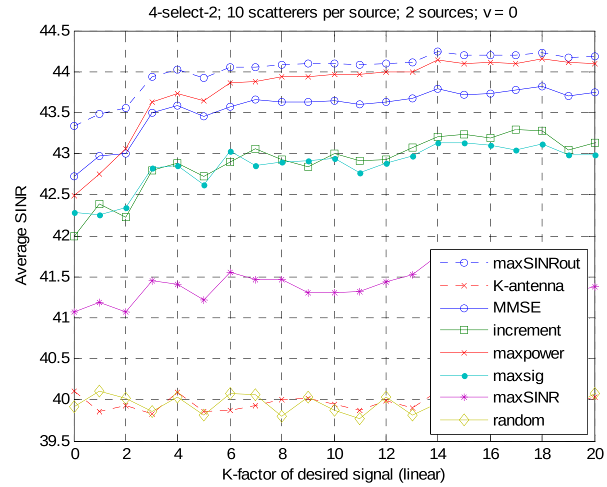

Figure 4. Average output SINR estimates for 4-select-2 architecture, 0 m/s, with 1 interference source, as a function of desired signal K-factor.

Similar results are found for other LOS configurations. For example, when the desired signal is NLOS and the interference has a K-factor of 20dB, the performance is very close to that shown in Figure 2 except that the maximum power algorithm does not perform as well, but is still slightly better than the MMSE curve.

Consider now the effect of mobility. Let each transmit node and the receive array be moving at a speed of 100m/s. The results for the NLOS case are shown in Figure 5.

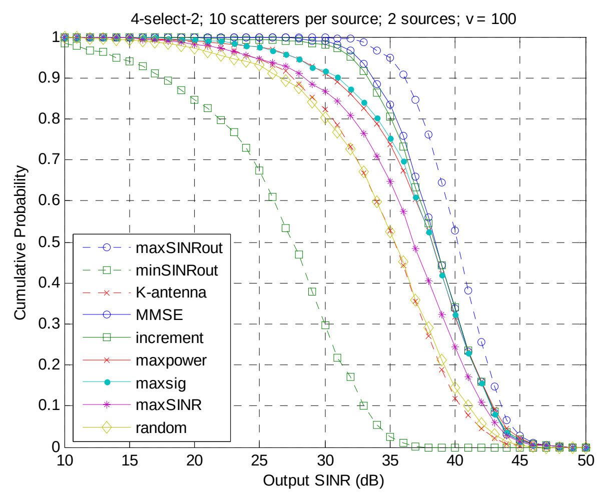

Figure 5. CCDF estimates of output SINR for 4-select-2 architecture, 100 m/s, with 1 interference source, and NLOS conditions.

The overall performance degrades somewhat compared to the static case, but the relative merit of the various downselection algorithms remains about the same. However, in this case, the performance of the MMSE and incremental algorithms is almost identical. In general, the velocity of the mobiles has minimal impact on the incremental algorithm, so in a highly mobile NLOS environment, the incremental is likely a good choice for downselection.

Consider the LOS case in a mobile environment, illustrated in Figure 6. Here, the desired signal experiences a Ricean K-factor of 20dB and the interference remains NLOS. Notice once again the superior performance of the maximum power criterion.

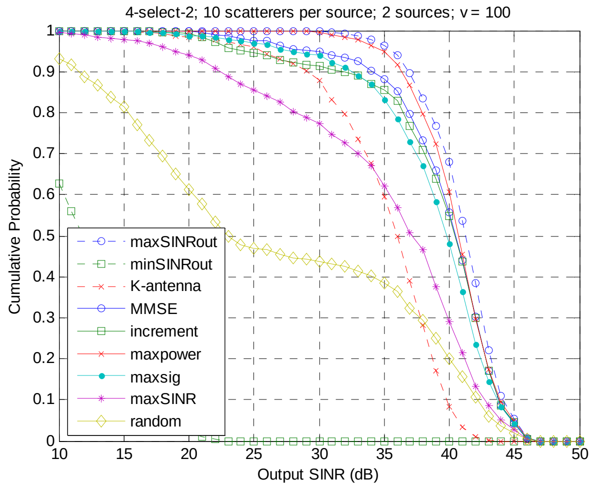

Figure 6. CCDF estimates of output SINR for 4-select-2 architecture, 100 m/s, with 1 interference source, and LOS conditions for the desired signal.

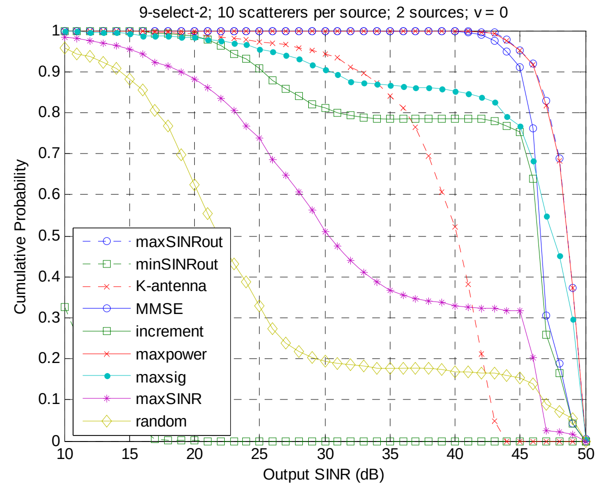

Figure 8. CCDF estimates of output SINR for 9-select-2 architecture, 0 m/s, with 1 interference source, and LOS conditions for the desired signal.

Nine antenna architecture; two element processing

Consider now a larger receive array with nine sectored elements of non-overlapping beams. By selecting two of the nine elements, the performance can be significantly improved relative to the 2-element sectored array with optimal combining. The static NLOS case is shown in Figure 7.

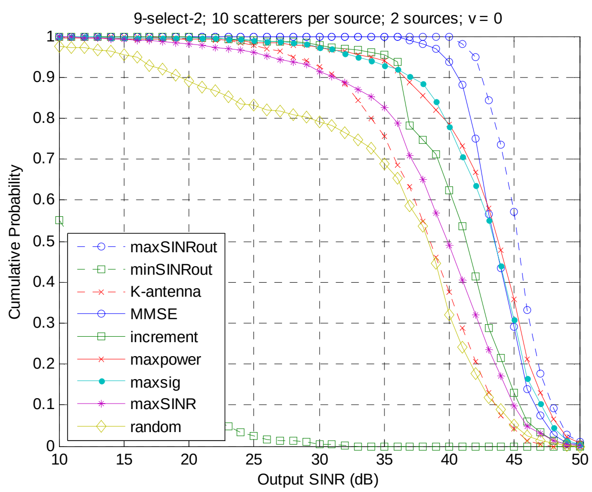

Figure 7. CCDF estimates of output SINR for 9-select-2 architecture, 0 m/s, with 1 interference source, and NLOS conditions.

Once again, consider the case where the desired signal is LOS with a Ricean K-factor of 20dB, illustrated in Figure 8.

As in the previous configuration, the maximum power selection algorithm performs extremely well in the LOS environment.

In general, if a LOS condition is expected for the signal of interest or the interference, the best technique for selecting antennas may be to measure the power at each of the N antennas with a coupler and diode detector and select the K antennas with the largest estimated power levels. This approach would not require any processing of the N-antenna signals to determine the selection choice and will usually yield very favorable results. In a static environment, this is almost the equivalent of pointing a directional antenna at the transmitter, but in a mobile-to-mobile environment, the LOS signal would be expected to move from one sector to another over time.

VI. Conclusion

Multiple antenna architectures have been investigated and their performance evaluated in a wireless mobile-to-mobile channel in the presence of co-channel interference. Using multiple antennas with down-selection at the receiver followed by optimal combining has been found to outperform optimal combining in a conventional sectored system where the number of antennas used in the adaptive processing is kept constant for comparison. Results from architectures using four and nine antennas with down-selection to two antennas were presented to show the performance improvement associated with increased antenna diversity.

Five down-selection algorithms were proposed in all, one based on the estimated MSE, which is typically the best performing for the NLOS case. When a LOS signal is present from either the desired signal or interference, a simple downselection technique based on power is found to perform very well, usually outperforming the MMSE algorithm. In a NLOS condition, the choice of an algorithm will depend on the constraints of the system and the expected environment. Candidate algorithms include the MMSE, incremental, and maximum power criteria.

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