CHAPTER 5
STRATEGIES FOR SYSTEM PERFORMANCE IMPROVEMENT USING MULTI-POLARIZED ARRAYS

Multi-polarized arrays combined with adaptive beamforming techniques promise improved quality in wireless communication systems through reduction of fading and mitigation of polarization mismatch caused by the random orientation of portable handsets. An increase in capacity may be possible in some systems by reusing frequencies with some combination of spatial- and polarization-division multiple access (SDMA/PDMA). Multi-polarized array performance at base stations for mobile communications has been simulated [5.1]. Similar techniques have been applied to terrestrial microwave links. Significantly, no measurements of multi-polarized adaptive array performance at base stations or mobile units have been reported, and no articles have been published on multi-polarized adaptive arrays for hand held units.

5.1 Diversity and Reuse Concepts

To understand the potential benefits of multi-polarized arrays (also called polarization-sensitive arrays) it is necessary to look at the concepts of diversity and reuse. In diversity combining, fading is overcome by extracting redundant information from some system resource. Each diversity branch beyond the first uses up a degree of freedom. “Extra” degrees of freedom in system resources can also be used to achieve reuse, or multiple access as discussed in Chapter 2. Resources that can be reused include space (geographical location and angular), time, frequency, and polarization.

5.1.1 Diversity

In a fading channel, signals from two receiver branches using orthogonally polarized antennas are uncorrelated or have very low correlation. It is unlikely that both branches will experience a fade at the same time. Because of this property it is possible to overcome most fades by selecting or combining the branches as shown in Fig. 5-1 to maximize received signal strength. Polarization is not the only mechanism that can be used for diversity. Spatially separated antennas and antennas that have different directional patterns also exhibit uncorrelated fading in many channels and can be used for diversity. Frequency diversity, in which the same signal is transmitted on two or more frequencies, is also possible. While only two (or at most three) orthogonal polarizations are available, diversity combining in general can be done for any number of branches.

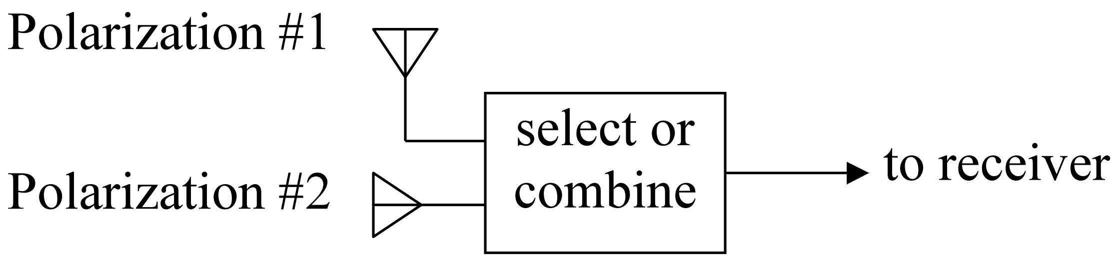

Figure 5-1. Polarization diversity

There are three basic diversity combining techniques. The first is *selection diversity*, in which the branch having the highest instantaneous received signal level is selected. The second is *equal gain combining*, in which signals from all branches are co-phased and combined. The third diversity technique is *maximal ratio combining*, in which signals on each branch are weighted proportionally to the SNR on that branch before co-phasing and combining. These techniques are described in [Jakes]. The latter two techniques, when used with spatially separated antennas, result in phased arrays.

The measure of diversity performance is diversity gain. This is the improvement in the signal level that is exceeded with a given probability, e.g. 99%, when diversity is used compared to the signal level that is exceeded with the same probability when diversity combining is not used. A general rule is that a significant diversity gain can be obtained when the correlation between signal envelopes on different branches is less than 0.7. All diversity techniques function best when the mean signal power levels on the branches are nearly equal.

5.1.2 Reuse and multiple access

The capacity of any wireless communication system is limited by the availability of resources. The scarcest resource is almost always frequency spectrum. Any resource that can be used to create multiple physical channels that occupy the same fixed block of spectrum will increase the capacity of the system. This is often referred to as reuse. In contrast, multiple access refers to the efficient subdivision of a single physical channel that occupies a fixed block of spectrum into several lower-capacity channels. While reuse and multiple access are conceptually distinct, the terms are used somewhat interchangeably. In fact there is some tradeoff between the two because either reuse or multiple access is likely to result in some interference between channels. The distinction is further confused in practice because some systems, such as CDMA cellular, use the same technology to facilitate frequency reuse and multiple access. These concepts are fundamental to wireless communication and were also discussed in Chapter 2.

Spatial separation is used for frequency reuse in cellular telephone systems. The same frequency is reused in different geographical areas, or cells. Cells using the same frequency are separated by a sufficient distance so that co-channel interference is at an acceptably low level. With directional adaptive antennas, angular separation can also be employed to reuse frequencies. This is referred to as "spatial division multiple access" or SDMA. Polarization is a resource which is exploited for frequency reuse in geostationary satellite and fixed terrestrial microwave systems. It has not been used in mobile systems, though this has been proposed [5.1]. Multi-polarized arrays with rapid adaptation would be needed to achieve Polarization reuse or PDMA in mobile systems because mobile channels typically exhibit multipath propagation and change rapidly as a user moves. PDMA would be easiest to implement in systems where the mobiles are pedestrians with handheld units, and the channel changes more slowly.

In frequency division multiple access (FDMA), the available spectrum is subdivided into narrower frequency bands, each of which is used as a channel.. Time division multiple access (TDMA) is used in some digital systems, usually in conjunction with FDMA. Each user on a given frequency channel is assigned one or more time slots within a frame and the data or digitized voice for that user is sent during these time slots. The use of a frequency at different times of the day by different callers can be conceptualized as an unmanaged form of TDMA that allows a system to serve many more users than the total number of channels. This is referred to as *trunking*. Trunking becomes more efficient as the number of available channels grows. In code division multiple access (CDMA), users transmit using direct sequence spread spectrum modulation with each user using a different pseudonoise PN code to spread the signal. Many users can share a frequency channel as long as their codes are different and have low cross correlations. The receiver sorts out the desired user by correlating the received signal with the appropriate PN code.

Various multiple access and reuse strategies can be used in combination. Examples are FDMA/TDMA, CDMA/SDMA or pseudo-SDMA, and the combination of FDMA and PDMA used in some satellite systems. Table 5-1 contrasts the use of these resources for reuse/multiple access and diversity, and includes examples and tradeoffs.

Table 5-1 Reuse and Diversity Mechanisms

Domain	Multiple Access (Reuse)			Diversity (Fading Mitigation)		
	Example	**Applicability**	**Comments**	**Example**	**Applicability**	**Comments**
Frequency	FDMA	analog or digital	Trade off signal quality/data rate vs. capacity	Frequency Diversity	Analog or digital	Spectrally inefficient
Space	Cellular frequency reuse	analog or digital	Trade off signal quality/data rate and coverage vs. capacity	Spatial Diversity	Analog or digital	Potentially large space requirements at low frequencies. Space requirements may differ for base and mobile
Time	TDMA	digital	Trade off signal quality/data rate vs. capacity	Retransmission, FEC with interleaving	Analog or digital (retransmission), Digital (FEC w/ interleaving)	Retransmission is slow. FEC w/ interleaving is combined time and code diversity
Code	CDMA	spread spectrum digital	Trade off signal quality/data rate vs. capacity	FEC with interleaving	Digital	See above
Angle	SDMA using adaptive antennas	analog or digital	Trade off signal quality/data rate, capacity, and size and complexity of antenna system	Pattern Diversity (gain or phase)	Analog or digital	Relatively new, works best if angle spread of multipath is fairly wide
Polarization	PDMA	analog or digital	Two polarizations can coexist in one frequency/space/time/ code/angle channel	Polarization Diversity	Analog or digital	Large unbalance and low diversity gain if polarizations are not chosen carefully. Helps mitigate polarization mismatch in systems with hand held mobiles

5.2 Previous Research on Multi-Polarized Adaptive Arrays

A multi-polarized adaptive array is simply an adaptive array of two or more elements, in which not all elements have the same polarization. Typically orthogonal polarizations are used, as shown in Fig. 5-2. Multi-polarized arrays have been considered as a means of rejecting jammer signals in military applications [5.2]-[5.4]. More recently, the potential of multi-polarized arrays for interference rejection in wireless communication systems has been investigated [5.5]-[5.9]. The related topic of cross-polarized interference cancellation (XPIC) used to improve polarization reuse in point-to-point microwave links is addressed in [5.10]-[5.16].

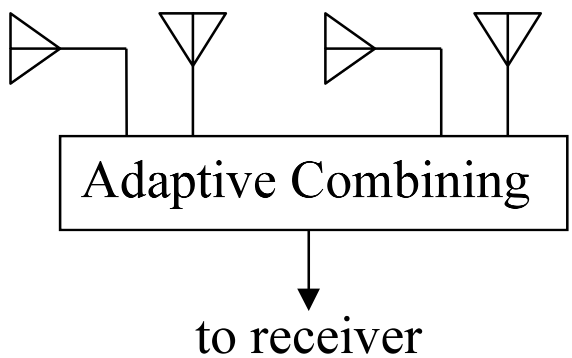

Figure 5-2. A multi-polarized adaptive array

In [5.2] an LMS adaptive array consisting of two pairs of crossed dipoles was simulated using a computer. The array configuration is shown in Fig. 5-3. The simulations used elliptically polarized desired and interfering signals with identical ellipticities but different tilt angles.

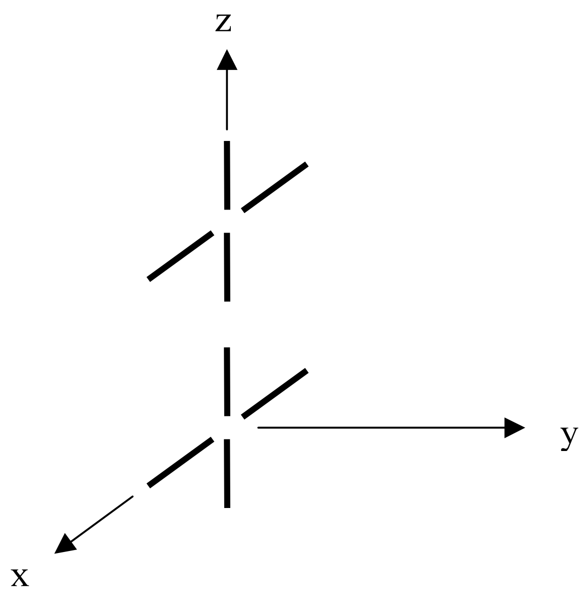

Figure 5-3. The multi-polarized array used in [5.2]

With the desired signal angle of arrival fixed at $(\theta_d,\phi_d)=(90°,90°)$, where the subscript "d" denotes the desired signal, $SINR_{out}$ was plotted vs. interferer azimuth and elevation angle for desired and interfering signals having different relative tilt angles. It was found that the SINR improvement with the adaptive array was greater than 35 dB for most interfering polarization tilt angles and greater than 20 dB for a difference in polarization tilt angles of only 5°. With both desired and interfering signals broadside to the array, It was shown that $SINR_{out}$ is a function of the separation of the two polarization states on the Poincare' sphere. If the desired transmitter and the jammer are both horizontally polarized or both vertically polarized and the elevation angle of the desired signal and jammer are the same, the array cannot cancel the jammer for any azimuth angle. This problem could be overcome by adding strategically placed elements to the array.

In [5.2], a "tripole" array is proposed. This array consists of three dipoles positioned along mutually orthogonal axes, as shown in Fig. 5-4. This antenna can match or null the polarization of a wave having any polarization state and incident from any angle in three dimensional space.

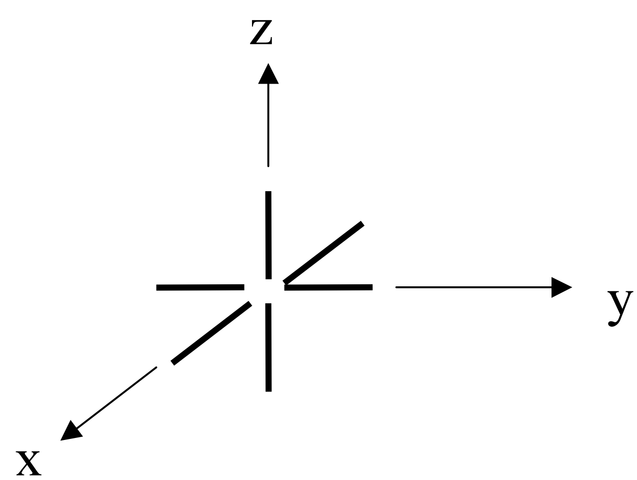

Figure 5-4. The "tripole" array [5.2]

In simulations similar to those of [5.2], the tripole provided an SINR improvement of greater than 30 dB in most cases. There were some special cases for which this antenna did not work well. These were as follows: (1)*Identical desired and interfering signal angles of arrival* In this case the performance of the array depends solely on the separation of the polarization states on the Poincare sphere. (2) *Opposite desired and interfering signal angles of arrival* In this case the performance of the array depends on the separation of the interfering signal polarization state and the conjugate of the desired signal polarization state. (3) *Linearly polarized desired signal* In this case the array cannot cancel an interferer that has a polarization parallel to that of the desired signal and that is incident from any direction in a plane that passes through the center of the array and is perpendicular to the polarization of the desired signal. An elliptically polarized signal does not present the same problems, but if linearly polarized signals are used, an array of tripoles is proposed to eliminate this vulnerability by providing more degrees of freedom.

The performance of a tripole adaptive array in the presence of orthogonally polarized ucorrelated jamming signals is simulated in [5.4]. If the desired signal is circularly polarized the SINR improvement is greater than 30 dB. The performance with a linear polarized desired signal is much worse. If the angle of arrival of the jammers is the same as that of the desired signal, the tripole antenna has only one degree of freedom to null an interfering signal and thus cannot null the two cross-polarized jammers. If the angle of arrival of the jammer is different from that of the desired signal, the tripole has two degrees of freedom and can null both jammers. Performance is also limited by noise.

The array antenna proposed in [5.5] consists of vertically and horizontally polarized elements mounted on a cylinder. Six arrays of five elements each are used. A conjugate gradient algorithm with constrained gain is used on the uplink only. The elements are 3 cm long and operate at 860 MHz ($\lambda/10$). The authors propose to implement polarization diversity by switching between vertical and horizontal polarizations every 1 ms and then adaptively varying the rate. The patterns shown are six bi-directional 30° beams covering 360°. Interference reduction results are not given.

An LMS array with arbitrarily spaced and oriented dipole elements is considered in [5.6]. The signal vector is derived from the geometry. Numerical results were presented but are not shown in the conference record.

In [5.7], a receive-only linear array of 12 dipoles with alternating polarizations is used for receiving an arbitrarily polarized wave. The element spacing is 0.576 λ. This was considered sufficient to minimize mutual coupling. A single vertically polarized dipole antenna was used at the transmitter. Data were sampled at 3.456 MHz on 12 channels using a system with a storage rate of 82.944 MHz. A blind adaptive algorithm was used to process the data. The signals were in DECT TDMA/GMSK format. With no interference present, switched diversity produced a 3.5 dB improvement in SNR and the blind equalization produced a 9 dB improvement.

The receiving antenna polarization that maximizes SINR is determined in [5.8] for an arbitrarily polarized interfering signal and thermal noise. Polarization mismatch is defined in terms of the Poincare' sphere. This paper gives a theoretical best polarization and SINR. The optimal polarization results in higher SINR than either matching the polarization of the desired signal or nulling the interfering signal.

In [5.9] a multi-polarized array that consists of four pairs of crossed dipoles is considered. The array was used with and without a flat-backed corner reflector as shown in Fig. 5-5.

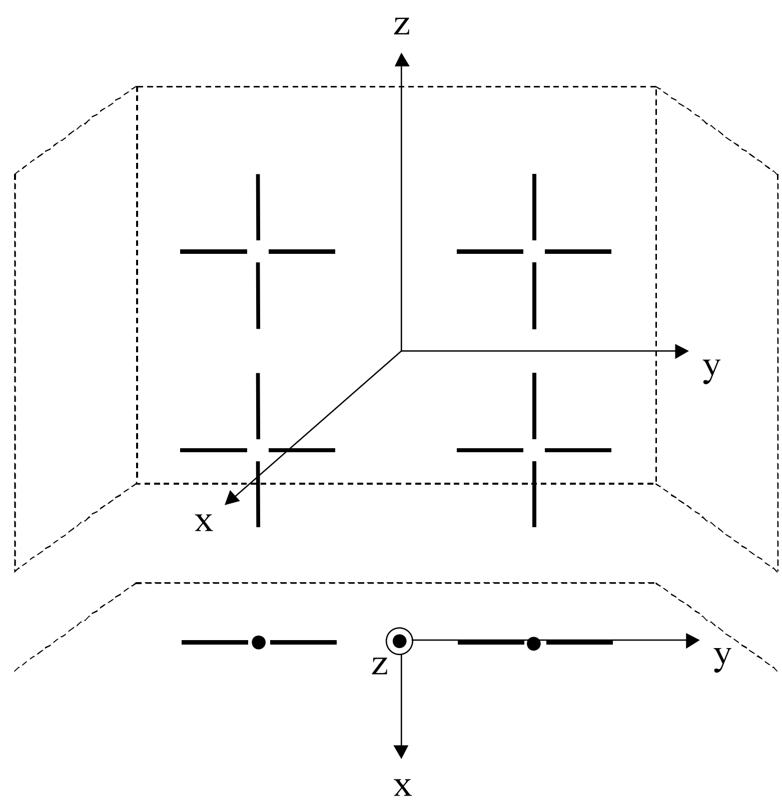

Figure 5-5. The multi-polarized adaptive array investigated in [5.9]

Mutual coupling effects are modeled using a method of moments computer code. With the corner reflector the array has a half power beamwidth of approximately 42° in elevation and 21° in azimuth. Sidelobe levels are -10 dB in elevation and -5 dB in azimuth. For identical desired and interfering signal polarization states, with the desired signal at broadside, the array provided an SINR improvement of 20dB for a ±3° difference in azimuth or elevation angles, and 30 dB for a ±10° difference. For a 15° difference in polarization angle, the array provides 30 dB SINR improvement without the reflector. The same SINR improvement can be achieved for a 10° difference in polarization angle if the reflector is used. SINR was significantly degraded in cases with 2 or 3 interferers.

In [5.10], the LSCMA algorithm and variations are proposed for cross polarized interference cancellation (XPIC). Real and multitarget variations of the algorithm are considered. Digital and hybrid implementations are shown. Two scenarios were simulated, one for intrasystem interference and another for intersystem interference. In the first scenario two 16 kHz MSK signals having a 45° degree difference in polarization tilt angle coexist on the same frequency. Each signal has a 20 dB SNR and 23dB Eb/No. Accounting for polarization mismatch, $SINR_{in} \approx 3$dB.

In the second scenario, a 16 kHz MSK signal experiences interference from a narrowband FM interferer that has a polarization tilt angle differing by 22.5 degrees from that of the MSK signal. In this case the SNR is 20 dB and the INR is 40 dB. With polarization mismatch this results in $SINR_{in} \approx -19$dB. Complex LSCMA using a 32 sample block and real LSCMA using a 64 sample block are compared with a 3 stage 1-2 SDCMA algorithm. A 1 kHz weight update rate is used. LSCMA converged to nearly optimum weights in 2-3 ms. In the intrasystem interference scenario, the $SINR_{out}$ was 20dB, an improvement of 17 dB, using the complex algorithm and 14 dB, an 11 dB improvement in SINR, using the real algorithm. In the intersystem scenario the complex algorithm yielded an improvement of 35 dB ($SINR_{out}$=14 dB) and the real algorithm improved SINR by 28 dB ($SINR_{out}$=9 dB). SINR improvements reported in the paper are compared to initial values of SINR when the algorithms are started. In the intrasystem scenario these do not match the calculated $SINR_{in}$. The $SINR_{out}$ with LSCMA was within 1 dB of the theoretical maximum and performance was better than with the SDCMA algorithm.

The only paper to propose using polarization sensitive arrays in a commercial mobile system is [5.1]. The arrays used at the base and mobile consist of vertical and horizontal elements with cross polarized interference cancellation (XPIC) using an RLS algorithm. This paper considers vertical and horizontally polarized signals in a Rayleigh fading channel. Co- and cross-polarized coupling are present and are modeled as complex Gaussian (Rayleigh envelope) random variables. TDMA signals with a training sequence of 20 symbols are simulated. The algorithm generates a replica of the signals and estimates the channel. Simulations were done for a flat Rayleigh fading channel with one path. The 384 kbps QPSK signals were detected coherently. Each time slot was 120 symbols long. The doppler frequency was less than 10 Hz. It was assumed that the system had power control to remove variations in the signal due to shadowing. Complex transmission coefficients are Rayleigh distributed and uncorellated. The cross polarization discrimination (XPD) was 5 dB. The XPIC worked best when the vertical to horizontal (V/H) ratio was about 0 dB. BER was found to be highly dependent on V/H in a static channel but less so in a Rayleigh channel. The XPIC improved BER by about an order of magnitude for XPD=0-30 dB when V/H=0 dB. The improvement was less for XPD greater than 30 dB.

In [5.11], a cross-polarized interference canceller (XPIC) is proposed for dual-polarization digital microwave systems. This paper reports on software simulations and field evaluations of a system using a decision directed algorithm. The system uses transversal filters that are optimized to minimize the correlation between the sampled cross-pol signal and the error signal from a decision circuit. An LMS algorithm is used. Simulations showed that in a flat-fading radio channel the performance of a dual-polarized system with an interference canceller was comparable to that of a single-polarization system. Cross-polarization interference due to the channel and the hardware was modeled. A field trial was performed over about one month in which every second containing bit errors was logged. Results from three receivers are compared. One receiver had no cross-pol canceller, another had a cross-pol canceller, and the third had a cross-pol canceller and an error-correction circuit. The receiver with cross-pol cancellation and error correction yielded error free results for 95% of the seconds in which errors were logged for the receiver with no cross-pol cancellation. Taps in the filter were fractionally spaced at one half the baud period so cancellation would be effective for all possible relative delays.

Another paper [5.12] considers joint intersymbol interference and cross-polarized interference cancellation for dual-polarized digital microwave systems. Frequency-selective fading is considered. Several receiver structures of comparable complexity are simulated including a linear receiver, an ideal canceller, and a decision feedback receiver (DFR). The ideal canceller performed best, but practical cancellers were highly dependent on the initial decision stage and did not perform much better than the DFR.

In [5.13], linear least-mean-square equalization is applied to dual polarized fading radio channels. The performance of XPIC is analyzed. Fractionally spaced XPICs have advantages but suffer from long-term instabilities. The eigenvalue spread of fractionally spaced XPICs tends to be high, resulting in an ill-conditioned covariance matrix that can lead to coefficient drift and register overflows. A tap-leakage algorithm (TLA) is used to reduce the eigenvalue spread of a fractionally spaced LMS XPIC to eliminate this instability. Computer simulations were performed for a 140 Mbps 64-QAM microwave system in a two-ray frequency-selective fading channel with delay 6.3 ns and XPD=10 dB. The system used 7 taps in the equalization section and 5 taps in the cancellation section. The TLA stabilization introduces additional noise but the simulations show that the MSE is increased by only about 0.3 dB. The degradation in system performance is considered to be negligible.

In [5.14], a single chip LSI digital transversal equalizer and cross polarization canceller are used in a digital radio system. The system has four 100Mb/s carriers using 256 QAM. The receiver uses a phase detector, transversal equalizer, cross polarization interference canceller, and an FEC decoder. The system was tested on a 33.5 km path over water where the reflected component is only 2.2 dB below the direct component. The delay of the reflected component is 2.4 ns. The digital XPIC reduces the minimum input desired/undesired polarization ratio by 20 dB, for BER=10^{-4} and C/N=40dB, an XPIC improvement factor or XIF of 20 dB. This is 10 dB greater than the improvement achieved with an analog XPIC.

Cross polarization interference cancellation for QAM radio is also investigated in [5.15]. In this paper fractionally spaced transversal filters are used. Multipath delays of up to 30 ns are considered possible, though the delayed components may be 30 dB below the direct component. A two-path propagation model with delay and cross polarization is used. The XPICs are complex 5 tap fractionally spaced transversal filters. Adaptive time domain equalizers implemented with 7 tap baud spaced transversal filters controlled by a zero forcing algorithm are also used. Experiments were conducted using a 16 QAM 140 Mb/s system with a roll-off factor of 0.5. The channel was simulated in hardware. Carrier and clock frequencies were asynchronous. The XPIC improvement factor (XIF) was greater than 20 dB for S/N=35 dB and BER = 10^{-6} for zero delay between vertical and horizontal channels. XIF increased with the number of equalizer taps and decreased with increasing signal delay. XIF was at least 5 dB when a frequency selective channel with a 15 dB notch in the passband was considered, with the worst performance occurring when the notch was near the center frequency. The arrangement considered accommodates vertical and horizontal signals that are plesiochronous.

In [5.16], three configurations for baud-rate XIPCs are compared. These XPICs are used in parallel with ATDEs of the same electrical length. The ATDEs use a zero forcing algorithm. The three XPIC implementations are as follows. In Variant A, the XPIC is controlled by the MMSE algorithm and the input signals from both branches are sampled at the same instants. This approach will support plesiochronous operation. In Variant B the input signals are sampled independently at times determined by clock recovery on each branch. An elastic store is used to allow sampling at one time and reading at another. This approach does not allow plesiochronous operation. Variant C uses a zero-forcing algorithm to control the XPIC and uses the elastic store. Variants B and C performed best, with little difference between the two.

A comparison of the results of all the papers reviewed is given in Table 5-2. These results show that a 20-30 dB improvement in SINR is possible if the arrival angle or polarization tilt angle of the interfering signal differs by more than a few degrees from that of the desired signal.

Table 5-2. Summary of multi-polarized adaptive array and cross-polarized interference cancellation literature

Reference	Application	Array	SINR Improvement, dB	BER Improve-ment, dB	XIF
[5.2]	Anti-jam	Two pairs of crossed dipoles	20-35+ for >5° pol. tilt angle difference	N/A	N/A
[5.2]	Anti-jam	"tripole"	30+ for most pol. tilt angles, less in special cases	N/A	N/A
[5.4]	Anti-jam w/ two cross polarized jammers	"tripole"	30+ for most pol. tilt angles if desired signal is CP, not as good for close AOAs	N/A	N/A
[5.7]	SNR improvement of DECT signal with no interference	Linear dipole array: 6 VP, 6 HP dipoles	3.5 dB (selection diversity) 9 dB (blind eq.)	N/A	N/A
[5.9]	Anti-jam	four pairs of crossed dipoles, optional reflector	20-30 for 3-10° Az or El difference 30 for 10-15° pol. tilt angle difference	N/A	N/A
[5.10]	Polarization reuse for system using MSK signal	N/A, real and complex LSCMA	11-17 dB intrasystem scenario 28-35 dB narrowband interferer	N/A	N/A

Table 5-2. Summary of multi-polarized adaptive array and cross-polarized interference cancellation literature (continued)

Reference	Application	Array	SINR Improvement, dB	BER Improvement, dB	XIF
[5.1]	Polarization reuse for mobile	1 VP and 1 HP ant.	N/A	~1 order of magnitude	N/A
[5.11]	Pol. reuse for fixed microwave	1 VP and 1 HP ant. XPIC and error correction	N/A	95% reduction in errored seconds	N/A
[5.14]	Pol. reuse in 256 QAM, 400 Mbps microwave system (field trial)	1 VP and 1 HP ant. XPIC, equalizer, FEC	N/A	N/A	20 at BER=10^{-4}, C/N=40 dB
[5.15]	Pol. reuse in 64 QAM, 140 Mbps microwave system		N/A	N/A	>20 at BER=10^{-6}, C/N=35 dB
[5.16]	Pol. reuse in 64 QAM 166 Mbps microwave system	1 VP and 1 HP ant. XPIC, equalizer,			

5.3 Possible Deployments of Multi-Polarized Adaptive Arrays

Three ways that multi-polarized adaptive arrays could be deployed to improve the service quality or capacity of mobile communication systems are described in this section. In addition there are many possible implementations of multi-polarized adaptive arrays that should be evaluated in order to select a suitable design.

5.3.1 Array at base station only

A multi-polarized adaptive array could be installed at each base station in a system. Here the main benefit would be the ability to match the polarization of hand held units. This would improve the quality of the uplink, and would help increase the battery life of hand held units.

5.3.2 Arrays at base station and mobile/hand held units

Further system performance improvements are possible multi-polarized adaptive arrays are used at base stations and mobile or hand held units. These include fading mitigation and polarization matching on the downlink, and possibly PDMA/SDMA if adaptation is fast enough to track changing polarization in a multipath channel.

A PDMA/SDMA system would function as follows. On the downlink, the base station will transmit to each mobile unit using either vertical or horizontal polarization. This doubles the number of channels in the system. The mobiles will adaptively cancel the interfering polarization. Since XPD is in the range of 0-7 dB in urban environments, the C/I on the downlink will be degraded by 0.8 to 3 dB compared to a system using only one polarization. Each mobile will transmit using either a “vertical” or “horizontal” polarization. In the case of hand held units these polarizations will not be truly vertical or horizontal due to random antenna orientation. This results in an uplink C/I that is approximately 3 dB lower than that in a single-polarization system. If the base station arrays are directional as well as multi-polarized this degradation can be overcome easily using spatial interference cancellation.

5.3.3 Peer-to-peer systems

A peer-to-peer system using some combination of mobile and hand held transceivers could also benefit from multi-polarized adaptive arrays. They can overcome polarization mismatch and mitigate fading. In addition, some interference can be cancelled, further improving signal quality.

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