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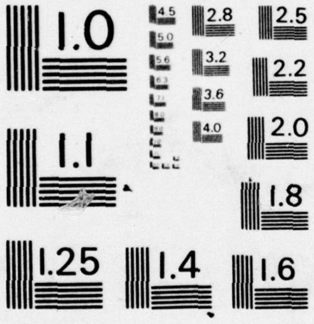

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Research and Development Technical Report

ECOM-4432

TECHNIQUES FOR ADAPTIVE CONTROL OF DIFFRACTION MODE AND TROPOSCATTER ANTENNAS

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September 1976

ECOM
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REPORT DOCUMENTATION PAGE

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⑭ 1. REPORT NUMBER ECOM-4432 ✓	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
⑥ 4. TITLE *(and Subtitle)* Techniques for Adaptive Control of Diffraction Mode and Troposcatter Antennas. ✓		⑨ 5. TYPE OF REPORT & PERIOD COVERED Interim rept.,
		6. PERFORMING ORG. REPORT NUMBER
⑩ 7. AUTHOR(s) George E./Krause Paul C./Ng		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS DRSEL-NL-RM-3 Communications/ADP Laboratory ✓ Fort Monmouth, N.J. 07703		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1X763707/D2451702
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Electronics Command Fort Monmouth, N.J. 07703		⑪ 12. REPORT DATE September 1976
		13. NUMBER OF PAGES 14
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)* ⑫ 18p.		15. SECURITY CLASS. *(of this report)* UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

Initial Report

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Adaptive Antenna Control; Beam Steering
Angle Diversity; Antenna Beam Steering
Troposcatter Communications

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

→ Beyond the horizon radio communications via troposcatter or diffraction modes are frequently troubled by bending of the RF rays due to changes in the atmospheric index of refraction. This can cause the received angle of arrival to appear outside the antenna's main lobe. A possible solution is to adapt the antenna's response to these changes. This report discusses possible state-of-the-art techniques, tradeoffs, potential problems and cost aspects for developing an adaptive antenna control system for use on existing troposcatter/diffraction mode antenna dishes. ←

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1. INTRODUCTION

Radio frequency signals propagated beyond the horizon may be diffracted by obstacles, or scattered by the troposphere. In the case of diffraction transmission, variation in the atmospheric index of refraction causes the apparent antenna beam to bend up or down resulting in reduced received signals and fadeouts. For tropospheric scatter transmission, variations in the atmospheric index of refraction give rise to variations in the angle of arrival of the signal at the receiving antenna which results in signal fading. This reduces the average received power and creates outages, deteriorating system reliability and performance.

Requirements in the Future Digital Network (FDN) call for improvement of the Defense Communications System (DCS) troposcatter and diffraction links to provide reliable wideband digital communication capabilities. The requirements on bit error rates (BER) vary from 1×10^{-8} to 5×10^{-5} depending on path length and desired availability.

The Defense Communications Agency (DCA) in its Systems Improvement Plan (SIP 1-75) tasked the Army to develop an adaptive antenna control technique to combat the fading caused by changes in the index of refraction (as discussed above). A letter of agreement (LOA) to implement the Army's accomplishing the task was signed by the Army Materiel Command (AMC)* and the Army Communications Command (ACC) on 19 June 1975. The Communications Systems Agency, a joint AMC-ACC organization, then tasked AMC's Electronics Command (ECOM) to perform the engineering effort on this program.

A. Program Objectives: The objectives of this program are to:

(1) Investigate the feasibility of an adaptive antenna control (AAC) system;

(2) Determine the optimum technique to accomplish AAC; and

(3) Implement and test a prototype of this technique on the RADC troposcatter test bed in upstate New York.

B. Program Parameters/Constraints: Since the AAC is being designed for operational equipment in the DCS, the following parameters/constraints are involved:

(1) Structural modifications will be limited to the feed system; the dish itself will not be altered;

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*Subsequently renamed Army Materiel Development and Readiness Command (DARCOM)

(2) A minimum performance improvement equivalent to one order of diversity must be attained;

(3) The system will operate on links with the following characteristics:

a. antenna reflector diameter to 60 feet, feedhorns at the focal point,

b. transmission frequencies from 600 MHz to 5.0 GHz,

c. smooth earth path lengths from approximately 100 to 320 nautical miles,

d. antenna beamwidths (at 3 dB points) from approximately 0.4° to 4.0°,

e. FDM/FM or digital signal processing,

f. bandwidths to 15 MHz,

g. transmitted RF power to 10 KW.

2. ADVANTAGES OF AN AUTOMATIC ANTENNA CONTROL SYSTEM

A. Technological Standpoint:

An AAC system will increase the time availability of the communication link. This will be accomplished by the ability of the antenna to adapt its maximum response to the direction of the maximum received signal power. As a result, the receiver signal to noise ratio will be increased and error rates subsequently decreased.

Moreover, the AAC system possesses the advantage of having the option to combine with space and/or frequency diversity techniques to achieve even higher quality of performance.

B. Economic Standpoint:

The AAC system would not require any major overhaul of existing systems. It is much less complex and expensive than a system employing space diversity in which two or more receiving antennas are used. The required frequency spectrum occupancy is much smaller than that for a frequency diversity system.

3. FEASIBILITY OF AN AUTOMATIC ANTENNA CONTROL SYSTEM

In July 1972, the U.S. Army ran a mechanical beam steering experiment on the DCA Schwartzwald-Savona radio link in Europe. During the experiment, the transmitting and receiving antenna feedhorns were steered mechanically in both the vertical and horizontal planes through a manual remote control arrangement. It was found that by steering the feedhorn(s), the average received signal power could be increased, thereby reducing propagation outages due to severe fading. An average signal level improvement of approximately 3 dB was obtained.

Research and experimental works by Waterman[1] showed that a narrow beam could be swung in quick succession through a limited angular sector by fast control of phasing, and the use of a broadside phased array. Phase and amplitude response patterns were obtained, and used to determine the direction in which the received signal level was maximum[2,3]. With state-of-the-art technology, it is feasible to automatically adapt antenna beam direction to the changes in the received signal angle of arrival.

An alternative to spatial movement of an antenna beam is a system which employs angle diversity techniques. It has been demonstrated by Monsen[4] as being capable of achieving performance comparable with that of space or frequency diversity. Experiments by Surenian[5] also indicated that angle diversity is comparable to space diversity in performance capabilities.

4. DESCRIPTION OF TECHNIQUES

The central problem is to adapt the antenna response to accommodate a changing transmission path for the transmitted signal. Conceptually, this can be accomplished by either fixing the direction of the transmitting antenna beam and adaptively adjusting the receiving antenna beam or by allowing the freedom for both transmitting and receiving antennae to determine optimum alignment. The adaptive control can be either the spatial movement of an antenna beam(s), or selecting/combining signals using diversity-type techniques. The individual choices are discussed in succeeding paragraphs.

A. Beam Steering Methods:

(1) Electronic Beam Steering: If the antenna beam is to be spatially steered, it is feasible to accomplish this via purely electronic means. One possible implementation would be the appropriate phasing of a multi-feedhorn system. The number of horns, their positioning, and the range of phasing would depend on the range of beam deviation required.

A predetermined threshold level for received signal strength would govern the decision whether or not to enter a beam change cycle. Determination of optimum beam orientation could be accomplished by incremental trial beam movements, or by utilizing a sensor technique. The sensor equipment is used to scan an angular sector in the direction of the arriving signal to obtain amplitude and phase information. A data processor could be used to calculate and determine the direction in which the received signal level is maximum. This is done at a rapid rate, which is dependent on the scan rate. Care must be taken to ensure that the scan rate is greater than the maximum fade rate (excluding fading due to aircraft in the common volume) of the communication channel. It should be in the order[3] of 20 scans/sec. Ideally, the control cycle rate should be the same as the scan rate. However, the control circuitry may oscillate and become unstable at a high rate. An acceptable solution is to use a control cycle as short as possible without causing oscillation, and to determine the direction at which the average signal power is maximum over the time period of the cycle.

As with all systems described here, the realignment sequences would be automatically implemented without operator intervention; however, a manual interrupt capability and a suitable real-time display of circuit performance would be included.

(2) Mechanical Beam Steering: Conceptually, mechanical systems would resemble the electronic implementation; however, there would now be physical movement of the feedhorn(s) to accomplish steering the beam.

The simplified beam steering concept is now complicated by the fact that on most DCA links, the antenna dish uses the same feed horn units for transmitting and receiving. It must be established that the optimum movement for receive is also the optimum movement for transmit if the unit is to be moved.

An analogous system to an electronic system for acquiring optimum beam alignment would be implemented. The incremental trial movement method would require physical movement of the feed horns. To implement a scan technique, it would probably be necessary to use multiple feed horns as in the phased array system of the electronic scan.

Servo systems would accomplish the physical movement of the feed horn(s) for beam direction changes, and it must be established that the response time is sufficiently short to allow adapting to beam wander.

B. <u>Angle Diversity Method:</u> In the troposcatter mode the common volume appears to contain multiple discrete scatters, which give rise to multiple ray paths that are relatively uncorrelated in their amplitudes and their fades. A significant increase in average signal strength can be achieved by simultaneously illuminating more than one area in the common volume, and diversity combining the various signals. One way to implement this is the use of multiple feed horns in a dish, arranged to produce multiple antenna lobes. This technique is commonly called angle diversity. To implement angle diversity on diffraction mode paths, it must be shown that multiple paths, with relatively uncorrelated fading characteristics, exist.

C. System Modes:

(1) Open-loop Control: For the open-loop configuration, with either electronic or mechanical beam steering, optimal performance is achieved by adaptively controlling the receiving antenna beam(s) based on received signal statistics.

(2) Closed-loop Control: As the name implies, the control information loop is completed by giving each terminal access to the results observed by both terminals when an adaptive change is made. The control channel must be made as reliable as possible, and designed such that a temporary signal degradation would not cause an interruption due to the need to re-establish the control loop.

The amount of feedback data that the control channel must carry will determine whether or not the present orderwire channels can be used for the purpose. Some type of data processing will be necessary to convert feedback data to antenna beam control information. To a degree, the round trip delay time, between antenna action and feedback reaction will determine the feasibility and effectiveness of closed loop techniques.

D. System Configurations:

(1) Steerable Single Beam: Operationally, a single antenna beam is steered in the direction of maximum received signal power. Sensor equipment, or incremental trial and error techniques, can be used to track the optimal beam pointing angle.

Such a system needs no combining circuitry and is relatively simple to implement. It can be implemented by either electronic or mechanical steering techniques, and can be controlled either open-loop or closed-loop.

(2) Fixed Multiple Beams: A fixed multiple beam system employs angle diversity techniques, as discussed in Section B. above. Care must be taken in determining the optimal pointing angle of each beam, to ensure that the correlation coefficients among the received signals from the diversity channels are less than about 0.6. This is due to the basic requirement of statistical independence among diversity channels in order to achieve quality performance.

Additional receivers and combining circuitry are necessary for implementing angle diversity.* The output of each receiver, corresponding to one diversity channel, is fed to the combiner. Various combining techniques can be used to enhance the received signal. Among them, maximal ratio combining and equal-gain combining techniques are more popular, whereas selection combining technique provides slightly lower performance. Care must be exercised in implementing the combining to avoid introducing errors in high data rate digital traffic.

(3) Steerable Multiple Beams: A steerable multiple beam system combines adaptive beam control and angle diversity techniques. The steerable range of each beam must be appropriately determined, and be such that the correlation coefficient between the signals of any two beams be less than about 0.6.

Multiple sensor equipments are needed to scan through predetermined angular sectors corresponding to the diversity channels. The optimal pointing angle of each beam could be determined by a data processor. Beam steering may be accomplished by either electronic or mechanical means.

Similar to angle diversity, multiple receivers are used* and the outputs are fed into a combiner for signal enhancement.

Theoretically, a steerable multiple beam system can achieve better performance than either a single steerable beam or a multiple fixed beam system.

5. COMPARISON OF TECHNIQUES AND TRADEOFFS

A. Electronic vs. Mechanical: Solid state technology offers a very convenient implementation of electronic techniques. It avoids mechanical wear-out of parts which implies an inherent reliability advantage. The response, since no mechanical inertia is involved, is many times faster, leaving little question as to its ability to track the variations in the angle of arrival of the strongest signal. Components likely to need maintenance or repair are more conveniently located.

Mechanical steering is not without advantages, however. It has been implemented on operational circuits and has shown an improvement in received signal level. There is no problem in proportioning high transmitter power (up to 10 kw) between/among feed horns, nor in physical placement of multi-horn arrays. Disadvantages include bending/flexing of waveguide to allow mechanical motion, and the inability to follow angle of arrival changes in a time frame shorter than seconds.

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*Assuming a post-detection system is used. Other circuitry would be necessary for a predetection technique.

B. Open-loop vs. Closed-loop Control: Open-loop control systems are simpler, and more economical to implement than closed-loop systems. A major advantage for closed loop control is that the results of transmitter antenna beam movements are available back at the transmitting terminal via the closed loop control channel. This is particularly important for a mechanical beam steering system since it is probable that the transmitting and receiving antenna horn(s) may physically move together. In an open loop system, it must not be assumed that the optimum orientation for both transmit and receive beams is coincident. Transmit and receive frequencies are normally well separated to insure that the high power of the transmitter does not disable its co-located receiver. It must be established that this frequency separation does not disrupt an assumption of coincident ray paths before coincident movement of transmit and receive beams is accepted.

It is possible that a mechanical or electronic beam steering open loop control system could experience excessive hunting. If one terminal realigns its feed horn structure to change its angle of arrival, it also changes its transmit angle (angle of launch). The distant terminal would notice a change in its angle of arrival due to the changed transmit angle at the original terminal. A realignment by the distant terminal could set up a hunting sequence. This type of hunting could be prevented in a properly instrumented closed-loop system wherein actions of each terminal are known by its partner.

Round-trip delay time, which can be in the order of 3 milliseconds (depending on path length, path geometry, and processing speed, etc.) is a factor to be considered in closed-loop control systems. It is to be determined whether delays of this order are significant. This in turn depends on how fast a fade rate the system will be designed to follow.

An obvious advantage of open-loop control is that it does not require a channel to send feedback information. This requirement is simplified for a closed-loop system if existing orderwire channels can be used, while still satisfying the reliability criteria.

The potential gain in circuit reliability for closed-loop control must be weighed against the advantages of a simplified system for the open-loop control.

C. Steerable Single Beam vs. Fixed Multiple Beams vs. Steerable Multiple Beams: A steerable single beam receiver offers the advantage of adaptive control, which maximizes the average received signal strength. Closed-loop control can be employed to further improve system performance. The need for a sensor equipment is offset by the fact that no combining circuitry is necessary. Choices for critical system parameters such as the scan rate for the sensor equipment and the decision criterion for beam movement, determine the maximum utility of the system.

A fixed multiple beam receiver employs angle diversity techniques, whose performance has been shown to approach those of space and frequency diversity techniques[4]. No sensor equipment is needed, but extra receivers and/or combining circuitry must be implemented. Proper choice of beam pointing angles is essential for successful operations.

A steerable multiple beam system includes both sensor and combining equipments, and is expensive and complicated to implement. To attain a favorable cost-performance ratio, it would have to produce substantial performance improvements over the other systems. Its complexity and cost are justifiable only on troublesome diffraction mode links that have an appreciable scatter component.

6. COST CONSIDERATIONS

In the preceding sections, the central problem and system philosophy have been stated. It is necessary to initiate a feasibility study and analysis to solve the problem. It should be arrived at via a contractual effort to include a design plan of the candidate technique, and a test plan to verify the performance improvement anticipated. The technique should be implemented and tested on a troposcatter test link. The test results should be documented in a final type report. Study, analysis, and design plan formulation would require about six months. Implementation, testing, and documentation would require an additional twelve months.

The cost of the AAC system may vary widely with the specific techniques. In evaluating the various techniques, it is important to consider cost effectiveness and tradeoffs. The following offers some insights.

A. Electronic vs. Mechanical: The state-of-the-art is relatively static for mechanical systems, in contrast to the dynamics of electronic development. The costs of implementing complex processing continues to decline, which indicates that electronic systems may be less expensive. Additionally, for many applications, electronic systems using solid state technology have proved inherently more reliable, and less costly to maintain. This impact on life cycle costs makes electronic implementation appear to be potentially less expensive.

B. Open-loop vs. Closed-loop: Closed loop control systems require a data processing capability for the data in the feedback loop. If the feedback data can be imposed on present orderwire circuits, there will be no impact on present trunking capability. The advantages discussed previously for closed-loop control are bought at a price of increased data processing and control equipment, plus a possible need for more orderwire capability.

C. System Configuration Comparison:

(1) Steerable single beam system: The complexity and cost of a steerable single beam system will vary according to its implementation. Some type of information processing capability will be necessary, but there is a choice, for example, between a scanning type sensor system and a trial-and-error approach. There is sufficient flexibility such that a well considered design could make the steerable single beam system attractive from both a cost and performance standpoint.

(2) Fixed multiple beam system: The fixed multiple beam system will probably be the closest rival to the steerable single beam system. The sensor system or trial-and-error technique would be replaced by an adaptation of well proven angle diversity techniques. Due consideration must be taken in the initial setup since the receiving lobes are fixed. Considering the fact that this technique has been shown experimentally to approach the performance of space or frequency diversity, the system promises to be competitive in performance with steerable single beam systems.

(3) Steerable multiple beam system: A steerable multiple beam system is more expensive to implement than either a steerable single beam or fixed multiple beam system, and would include all the necessary equipments for the other two configurations. The processor must have an algorithm able to follow fast (less than 1 second) fades. The added improvement for most links would probably not justify its cost and complexity.

7. POTENTIAL PROBLEMS

Many technical problems are expected in implementing an AAC system. The following are significant and probable examples:

A. Suboptimal threshold level for a decision to implement a beam movement cycle: When the threshold level is too high, oscillation of antenna beam position may occur; if it is too low, little or no adaptive control is accomplished.

B. Slow response time: System performance would be deteriorated if the antenna beam is not adapted to the desired or optimal pointing angle within a reasonably short instance of time, after control action is initiated. This may be due to hardware limitations and characterized by large overshoots.

C. Phase variations: Due to the differences in propagation path length, phase variations among signals from the diversity channels may deteriorate a system employing multiple beams.

E. Antenna feedhorn inertia (for mechanical steering only): Slow response time may reduce the advantages gained by adaptive control, if the servo mechanism is incapable of following the fast variations in optimal beam pointing angle.

F. Multiple feedhorns at antenna focal area: For a system with multiple feedhorns, it may be very difficult to physically place the feedhorns at the optimum location.

G. Multiple usage of antenna horn: For some DCS antennas, the same feedhorn system is being used for both transmission and receptions in, for example quad-diversity systems. For a system which employs an adaptive control scheme, the movement of the receiving beam may offset the optimum pointing angle of the transmitting beam. This problem may be exceptionally severe in an open-loop system, where no coordination exists between the transmitting and receiving antennas for determining the optimum orientation.

H. Switching time in selection combining: For a system with multiple beams employing selection combining, slow switching speed among the diversity channels may cause performance degradation. This problem becomes more acute for high data rates and fast fades.

I. Feedback information handling: In a closed-loop system, some communication channel must be allocated for the feedback loop. One possible solution is digitizing and superimposing the feedback information on the order wire circuit. However, problems such as insufficient reliability and excessive time delay may be encountered.

8. SUMMARY AND CONCLUSIONS

A. The feasibility of gaining significant signal enhancement by manually steering antenna beams to account for a changing angle of arrival was established by US ACC Europe over the Schwartzwald (Germany) - Savona (Italy) radio link.

B. Department of Army has been tasked by DCA to develop an adaptive antenna control system to adapt troposcatter and diffraction mode antenna response to changes in signal angle of arrival caused by changes in the atmospheric index of refraction.

C. There are several possible approaches, applicable to DCA antennas (dishes up to 60 ft. in diameter, with feedhorns at the focal point):

(1) mechanical techniques wherein feedhorns at/near the focal point are physically displaced,

(2) electronic techniques, wherein physical feedhorn movement is replaced by beam steering via phase array techniques,

(3) angle diversity wherein an antenna has two or more fixed main beams whose responses are diversity combined.

D. In designing an adaptive antenna control system, tradeoffs are possible, for example, closed loop vs. open loop control.

(1) Open loop control systems are less complex, and more economical to implement and maintain, however they are effective only in correcting receiver antenna response, whereas,

(2) Closed loop control can effectively adjust a transmitting antenna beam since it is aware of the effect on the receiving antenna of the adjustment. It is, however, more expensive and complex, and requires a highly reliable data channel.

E. Several potential problems suggest themselves and some are dependant on the particular approach. Potential problem areas include:

(1) a proper choice of a decision threshold,

(2) an adequate system response time,

(3) the phase variations among multipath signals (for high data rate transmissions), and

(4) the handling of feedback information.

9. RECOMMENDATIONS

It is recommended that a study be initiated to determine the feasibility of adaptively controlling the response of troposcatter and diffraction mode antennas, and to determine the optimum adaptive control technique.

Method: An effort should be initiated to:

(1) determine the optimum approach and prepare a design plan for a prototype of its hardware implementation, and

(2) prove its feasibility and determine its advantage by fabricating and laboratory testing the prototype. This would be followed by installing it on equipment in a test bed, to determine its advantage over a parallel uncontrolled circuit.

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