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A Novel Irrigation Control Technique using Aerial Wireless Sensor Network

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Abstract

In this paper, a novel irrigation wireless sensor network is proposed using high altitude platform (HAP) and an adaptive switched-beam concentric circular antenna array. This proposed wireless sensor network provides very wide area coverage that extends to several tenses of kilometers and therefore can bridge the difficulty of deploying wide area sensor networks by conventional techniques especially for hard terrain regions. On the other hand, the switched-beam antenna system provided by the proposed technique has very high gain with narrow main lobe and low sidelobe levels which supports the communications link between HAP and ground irrigation sensors and actuators over wide areas. Also, three current weighting profiles are examined in the proposed technique which are uniform, Hamming, and Cosine feeding profiles and all have provided high communications performance in terms of bit-energy to noise power spectral density which is more than 34 dB inside the coverage beam area at 868 MHz with 38.4 Kbps.

Keywords: High-Altitude Platforms, Antenna Arrays, Wireless Sensor Network.

INTRODUCTION

In recent years, various irrigation control systems are designed to improve water utilization especially for regions that suffer from the seldom water resources. Some of these control systems use water-saving irrigation techniques and scheduling of irrigation [1]. Several systems designs for controlling irrigation have been proposed in [2-10] including various hardware and software capabilities. The problem of deploying wireless sensor networks for irrigation control include the difficulty to cover wide areas especially for remote regions that span wide distances as in deserts and mountainous regions. On the other hand, the communications channel performance of ground wireless sensor networks suffers greatly from several impairments such as fading and rapid signal decay due to physical obstructions [11]. Satellite communications is one favorable solution to improve the communications performance but requires special infrastructure and high transmitting power which is not suitable for irrigation sensors and actuator systems. Recently, the idea of using high-altitude platforms (HAP) has gained attention inn several communications applications [12-13], where an aerial station in the form of airship or aeroplane flies in the stratosphere especially at 21 km altitude and can provide the same performance of satellite systems such as wide area coverage but at much less required transmitted power. The system performance can be further improved by concentrating the radiation pattern on the intended areas through adaptive antenna arrays. Therefore, in this paper the performance of wireless sensor network for irrigation control purposes is improved by combining the HAP technology with switched beam antenna arrays and the proposed system can bridge the network deployment gap especially for remote areas that suffer from the lack of communications infrastructure.

THE PROPOSED SYSTEM ARCHITECTURE AND ANTENNA TECHIQUE

In this section, the antenna system onboard HAP is designed to provide improved coverage for establishing WSN network for irrigation control. This antenna system is proposed to provide switched narrow beams that scan the whole irrigation area to be controlled and provide the communication between sensors and actuators on the ground and the global sink onboard HAP as shown in Figure 1. The antenna array is chosen to be in the form of concentric circular antenna arrays which provides many advantages over most of the antenna structures where it provides mostly uniform beam coverage over wide angles and easier feeding through windowing functions. The concentric circular antenna array (CCA) is demonstrated in the coming section in more details.

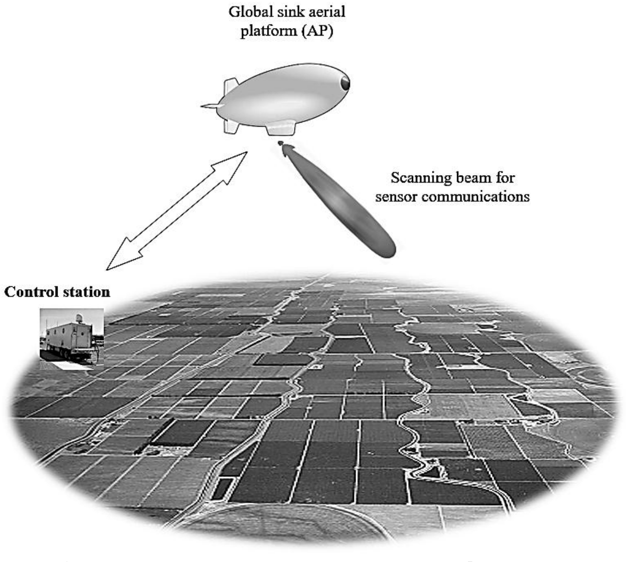

Figure 1: HAP-WSN Irrigation Control System

The arrangement of elements in CCA contains multiple concentric circular rings which differ in radius and number of elements and this gives arise to different radiation patterns. Figure 2 shows the configuration of CCA in which there are *M* concentric circular rings.

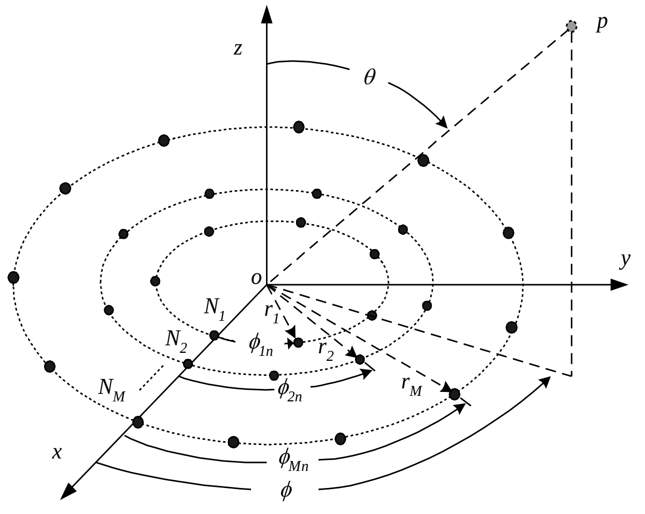

Figure 2: Geometry of concentric circular antenna array.

The m^{th} ring has a radius r_m and a number of elements N_m where $m=1,2,\ldots,M$. Assuming that the elements are uniformly spaced within the ring so it has an element angular separation given by:

$$\psi_m=\frac{2\pi}{N_m} \tag{1}$$

and the elements in this ring are therefore located with an azimuth angle measured from the x-axis given by:

$$\phi_{mn}=n\,\psi_m\,,\quad n=1,2,\ldots,N_m \tag{2}$$

Assuming an observation point *P* located at a distance *r* form the origin, the measured far field at this point will be:

$$E(r,\theta,\phi)=\frac{e^{-jkr}}{r}\sum_{m=1}^{M}\sum_{n=1}^{N_m} w_m\; e^{jkr_m\sin\theta\cos(\phi-\phi_{mn})} \tag{3}$$

where $k=2\pi/\lambda$ is the wave number and w_m is the excitation coefficient (amplitude and phase) of the m^{th} ring. From Eq. (3), we can deduce an expression for the array steering matrix by first defining the array steering vector for a single ring and extending the analysis for the whole array. The n^{th} element in the array steering vector for the m^{th} ring is given by:

$$s_{Cm}(\theta,\phi)=e^{jkr_m\sin\theta\cos(\phi-\phi_{mn})},n=1,2,\ldots,N_m \tag{4}$$

And the m^{th} ring array steering vector is given by:

$$S_{CM}(\theta,\phi)=[s_{C1}(\theta,\phi)\,s_{C2}(\theta,\phi)\ldots s_{CM}(\theta,\phi)]^T \tag{5}$$

and the array steering matrix can be formulated as:

$$A_{CCA}(\theta,\phi)=[S_{C1}(\theta,\phi)\,S_{C2}(\theta,\phi)\ldots S_{CM}(\theta,\phi)] \tag{6}$$

where we should append lower dimension in Eq. (6) with zeros.

We can control the radiation pattern of the array by controlling the magnitudes and phases of the exciting currents. Therefore, the array factor may be determined from the following equation:

$$G(\theta,\phi)=SUM\left\{W(\theta,\phi)^H A_{CCA}(\theta,\phi)\right\} \tag{7}$$

where the *SUM* operator is the summation of all elements in the resulted matrix $W(\theta,\phi)^H A_{CCA}(\theta,\phi)$, H is the complex conjugate transpose or Hermitian operator and $W(\theta,\phi)$ is the weight matrix that controls the amplitudes and phases of the input currents. If the ring weighting profile is given by $w(M)$, then the array weighting matrix can be written as follows:

$$W(\theta,\phi)=A_{CCA}(\theta_o,\phi_o)w(M) \tag{8}$$

COMMUNICATION LINK PERFORMANCE

In this section, the communications link between AP and irrigation sensors on the ground are described by a set of link equations where it depends on several parameters such as the environment of the sensors, the AP coverage diameter, transmitting frequency, bit rate and the length of the link distance. There are additional link parameters that also affect on the system performance such as the transmitting power, transmit and receive antenna gains and the atmospheric effects. One of the main evaluation parameters for this system is the bit energy-to-noise power spectral density, $E_b/N_o\ (\theta,\emptyset)$, which is very important in the calculation of the probability of error according to the applied modulation schemes. To determine this ratio we will first determine the received power at the AP antenna, $P_{rHAP}(\theta)$, which is a function of the look direction, θ , as follows:

$$P_{rHAP}(\theta,\emptyset)=P_{tS}G_{sS}G(\theta,\emptyset)/P_L(\theta,\emptyset) \tag{9}$$

where P_{tS} is the sensor transmitted power, G_{sS} is the sensor antenna gain, The last equation can be rewritten in dB as:

$$P_{rHAP}(\theta,\emptyset)[dB]=P_{tS}[dB]+G_{sS}[dB]+G(\theta,\emptyset)[dB]-P_L(\theta,\emptyset)[dB] \tag{10}$$

The propagation loss, $P_L(\theta,\emptyset)[dB]$, includes both the distance and shadowing losses:

$$P_L(\theta,\emptyset)\ [\mathrm{dB}]=P_L(\theta_o)\ [\mathrm{dB}]+10\,n_p\log(d(\theta,\emptyset)/d(\theta_o))+X_q \tag{11}$$

where n_p is the pathloss exponent, θ_o is a reference direction and $d(\theta_o,\emptyset)$ is its corresponding slant distance and $d(\theta,\emptyset)$ in the slant distance between the AP and the transmitting sensor with θ look direction using the following equation:

$$d(\theta,\emptyset)=h/\cos(\theta) \tag{12}$$

The reference propagation loss $P_L(\theta_o,\emptyset)$ in dB is calculated from the following equation:

$$P_L(\theta_o,\emptyset)=20\log(4\pi\, d(\theta_o,\emptyset)/\lambda) \tag{13}$$

The additional loss X_q represents the loss due to the shadowing effects and is characterized by a Gaussian random variable in dB with zero mean and standard deviation in dB also.

The value of n_p and standard deviation depend on the propagation environment where for free space propagation $n_p = 2$ and a typical value of standard deviation for AP radio coverage is 2 dB. The key performance measure, $E_b/N_o(\theta, \emptyset)$ [dB] is given by:

$$E_b/N_o\ (\theta, \emptyset)\ [\text{dB}] = P_{tS}\ [\text{dB}] + G_{sS}\ [\text{dB}] + G(\theta, \emptyset)\ [\text{dB}] - P_L(\theta, \emptyset)\ [\text{dB}] - N_o\ [\text{dB}] - R_b\ [\text{dB}] \qquad (14)$$

$E_b/N_o\ (\theta, \emptyset)$ [dB] can be improved by increasing the antenna gain either in the transmitting sensor node or at the HAP sink.

RESULTS AND DISCUSSION

We have examined six cases of the CCA for wireless sensor irrigation network using:

1- CCA with uniform feeding coefficients $w_U(m)$

$$w_U(m) = 1 \qquad (15)$$

2- CCA with Hamming feeding coefficients $w_H(m)$

$$w_H(m) = 0.54 + 0.46\cos\left(\frac{\pi(m-M-2)}{M+1}\right) \qquad (16)$$

3- CCA with Cosine feeding coefficients $w_C(m)$

$$w_C(m) = \cos\left(\frac{\pi}{M}\left(m - \frac{M}{2}\right)\right) \qquad (17)$$

In each case, the performance is described by the footprint distribution of E_b/N_o and the probability of E_b/N_o that is less than X for the central scanning beam for both inside the half-power contour and for the whole area.

Figure 3 depicts the possible footage of the scanning beam to cover and switch between different areas that correspond to a HAP at 20 kilometers high.

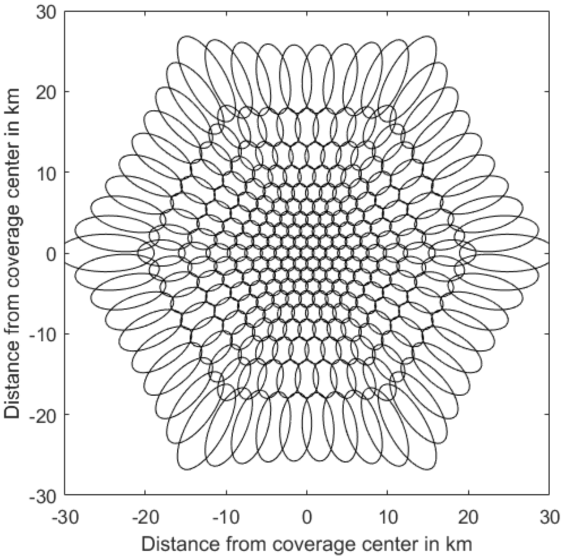

Figure 3: Typical scanning beam locations formed by an array onboard HAP at 20 km high. The scanned area can be simply extended by adding outer tiers.

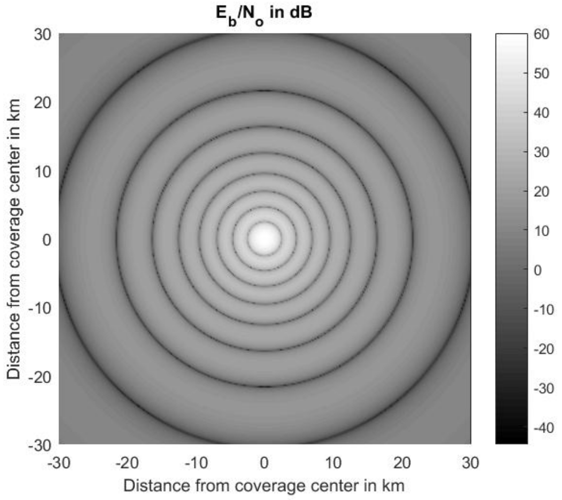

Figure 4: E_b/N_o footprint for the central beam coverage using uniform feeding

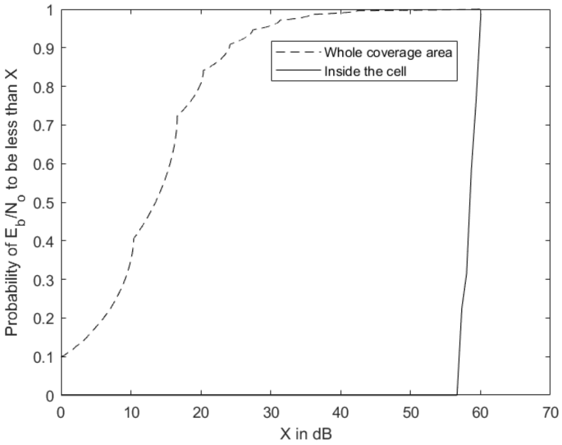

Figure 5: Probability of E_b/N_o that is less than X for the central beam coverage using uniform feeding

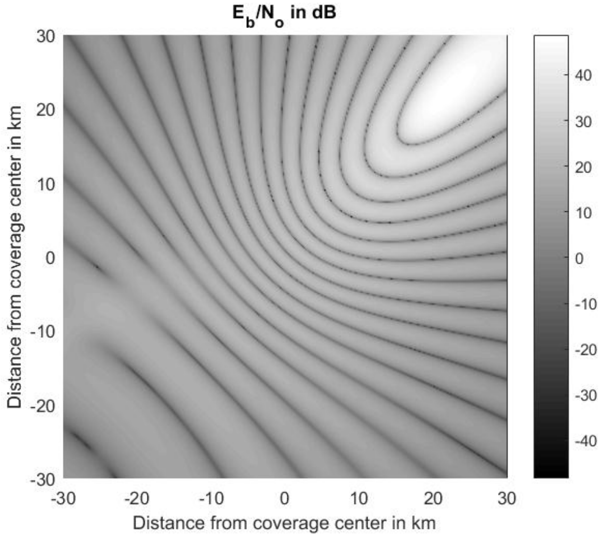

Figure 6: E_b/N_o footprint for the end-of coverage beam using uniform feeding

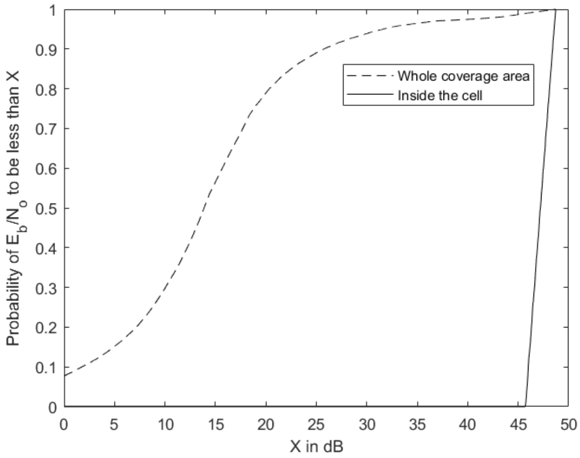

Figure 7: Probability of *E_b/N_o* that is less than X for the end-of coverage beam using uniform feeding

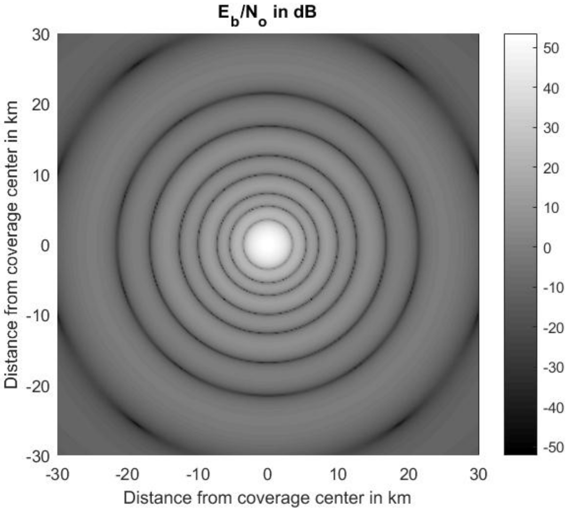

Figure 8: E_b/N_o footprint for the central beam coverage using Hamming feeding

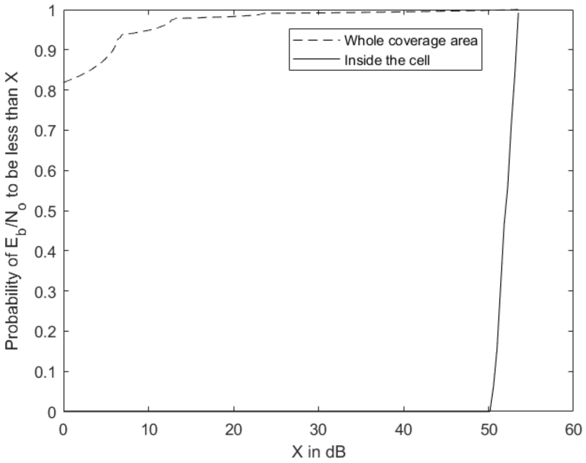

Figure 9: Probability of E_b/N_o that is less than X for the central beam coverage using Hamming feeding

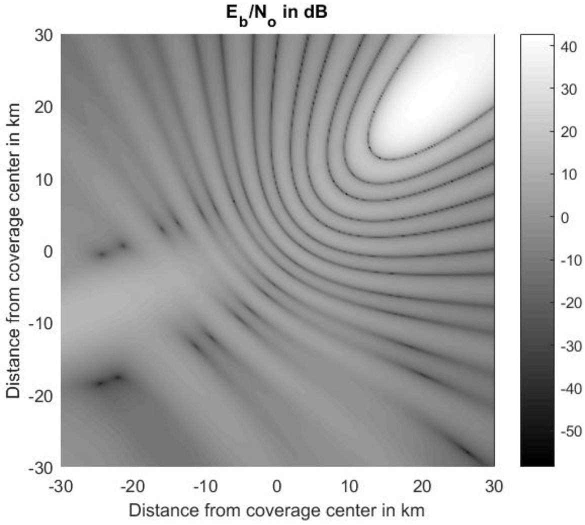

Figure 10: E_b/N_o footprint for the end-of coverage beam using Hamming feeding

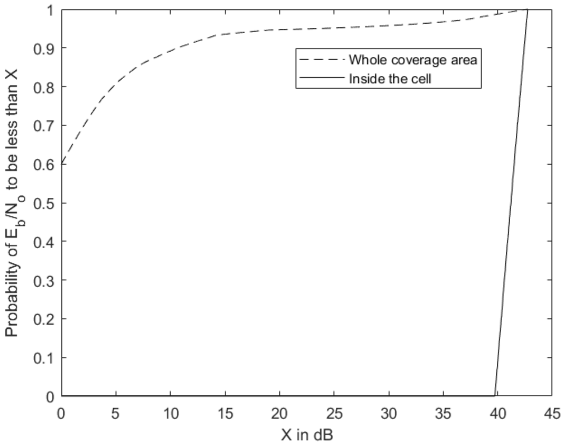

Figure 11: Probability of E_b/N_o that is less than X for the end-of coverage beam using Hamming feeding

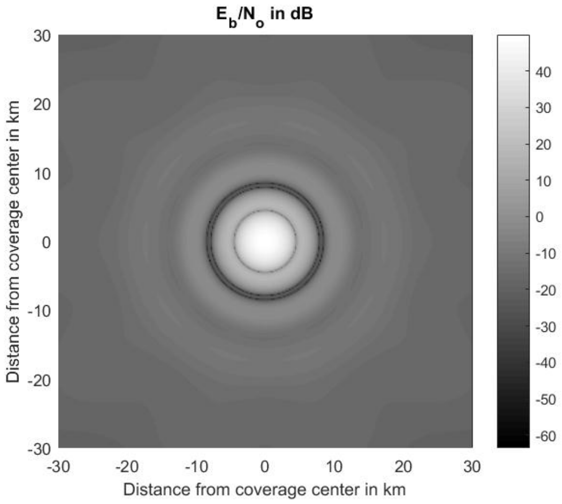

Figure 12: E_b/N_o footprint for the central beam coverage using Cosine feeding

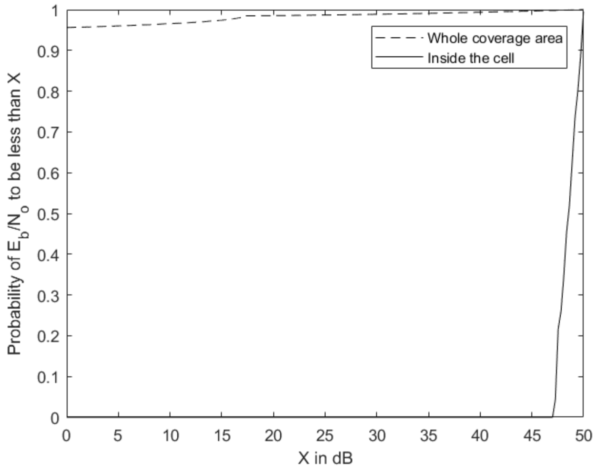

Figure 13: Probability of E_b/N_o that is less than X for the central beam coverage using Cosine feeding

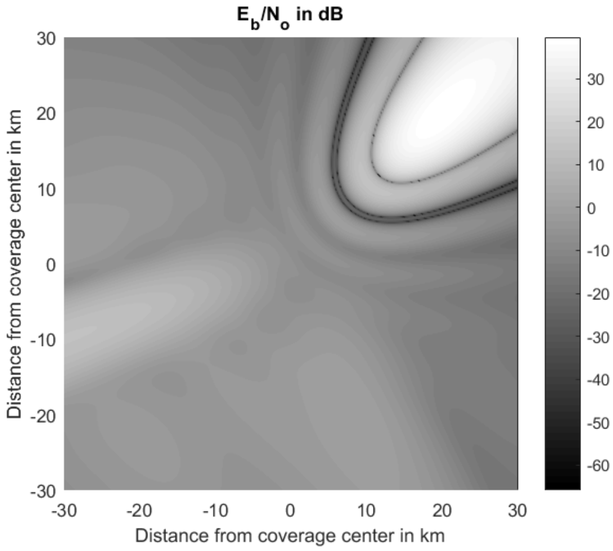

Figure 14: E_b/N_o footprint for the end-of coverage beam using Cosine feeding

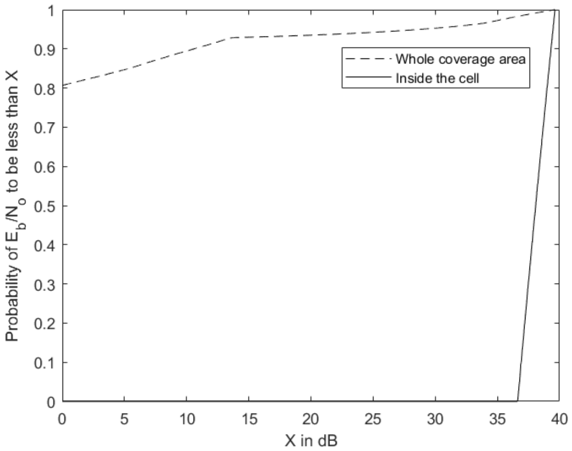

Figure 15: Probability of E_b/N_o that is less than X for the end-of coverage beam using Cosine feeding

The proposed switched-beam antenna system provides many advantages for this application such as the provision of high antenna gain to enable remote sensors for communications, lower out-of-coverage power gain (sidelobe levels) which is necessary to reduce the interference between neighboring broadcasting HAP irrigation control stations. The application of the proposed switched beam has also improved not only the received power levels but also the quality of the communications link as shown at different feeding profiles. The conventional substitute to the proposed irrigation control system is to use ground control which is very limited due to the terrains and also subjected to the terrestrial communications impairments.

Therefore, we can conclude some remarks about the proposed system as follows:

1- Wide area coverage has been achieved by the proposed system where a single HAP located at 20 km high can cover a circular area of 1000 km diameter which is very large compared to terrestrial irrigation control systems which almost cover up to only several kilometers.

2- The channel propagation characteristics in the proposed irrigation control HAP system are better than that in the conventional terrestrial wireless sensor networks where the path loss is inversely proportional to the square of the slant distance between the HAP and receiver while in the terrestrial systems it suffers from excessive multipath propagation and the path loss is inversely proportional to the distance raised to an exponent of 4.

3- Three feeding methods has been addressed starting from the simplest one which is the uniform feeding profile. This feeding profile provides the narrowest beamwidth among any other beamforming technique but suffers from the higher sidelobe levels which is critical to avoid miss-communications with other sensors in neighboring irrigation areas.

4- The results has shown high performance of the communications link even at the worst case of uniform feeding where the value of E_b/N_o is greater than 57 dB inside the coverage cell boundary as shown in Fig. 4 and its distribution falls gradually as shown in the same figure and also in Fig. 5 due to the higher sidelobe levels.

5- Even at the end-of-coverage scanning beam, the communications performance is superior inside the cell while the continuous gradual decreasing of E_b/N_o is still a main problem.

6- The problem of gradual degradation of E_b/N_o outside the coverage cell which may cause interference to other sensors has been solved by using tapered beamforming techniques such as Hamming and Cosine profiles as shown in Figs. 8 to 15.

7- The effects of using tapered feeding profiles include degradation in the E_b/N_o level inside the coverage beam boundary while it provides superior out-of-cell performance due to the lower sidelobe levels. The degradation of E_b/N_o outside the cell is therefore falling very rapidly which is seen by high probability of obtaining E_b/N_o to be less than X.

CONCLUSION

In this paper, an efficient and new system for irrigation control is provided using high-altitude platforms (HAP) and switched adaptive beamforming technique using concentric circular antenna arrays. This novel technique has been introduced for building wireless sensor networks using aerial platforms to control the amount of fresh water needed for irrigation through improved communications link performance over wider areas. Also the introduced antenna technique utilizes narrow main lobe which is directed towards sensors on the ground to maximize the battery life of these sensors especially for regions having limited energy sources. The coverage performance of the proposed system has been analyzed and investigated and the quality of communications link has been approved for three feeding array profiles. The provided high quality performance of communication in terms of bit energy to noise power spectral density between the aerial platform and the irrigation sensors and water valves on the ground over a large areas has been proved especially for tapered array feeding which cannot be provided by conventional smart irrigation techniques. The results have shown that a 10 rings concentric circular array with uniform feeding is capable of providing bit energy to noise power spectral density more than 57 dB for a central scanning beam at 868 MHz and 38.4 kbps which secures the communications at different weather conditions.

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