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A Novel Technique to Improve the Performance of Wireless Sensor Network using Adaptive Antennas and High-Altitude Platform

Yasser Albagory, Mostafa Nofal, Omar Said

Taif University,
College of Computers & Information Technology,
Information Technology Department
Taif, Saudi Arabia

Abstract— **In this paper, the concentric ring antenna array is developed to improve the communications link in wireless sensor networks. This technique is applied to the new Stratospheric Aerial Platform (SP) infrastructure for Sensor Networks. An adaptive current feeding for the array is applied. The simulation results show the possibility of communications between the SP sink station and sensor nodes located on the ground. The proposed ring array is optimized using a modified Dolph-Chebyshev feeding and comparison with conventional antenna models in literature shows the improvement in communications performance in terms of bit energy to noise power spectral density ratio by considerable.**

Index Terms— **High altitude platform;, wireless sensor network; directional antenna;, concentric circular arrays.**

I. INTRODUCTION

Recently, the importance of Wireless Sensor Network (WSN) has gained attention where it is applied in many applications including industrial manufacturing, military, agriculture, health care, and security [1-7]. The structure of this network contains a number of remote sensors that measure some data and forward it wirelessly to a collection point called sink. The distance between the sensors and the sink depends on the communication environment and the power available for sensors which usually comes from batteries. There are many challenges for the WSN such as the limited battery life time, wireless communication performance, routing and data security. The energy of sensors is the most important problem due to network-lifetime maximization target. Another main issue regarding WSN is the breadth of the coverage which depends on the communication technology applied between these sensor nodes and sinks especially the antenna types.

The ground-based WSN has a very limited communication range due to the channel impairments including multipath fading problems. The existing sensor technology has limited sink coverage to few meters due to the limited battery life time. The coverage range and battery life time can be extended by changing the type of communications channel to reduce the fading problem and namely using the free-space or line-of-sight model. Recently, the feasibility of covering large area WSN with Stratospheric Platforms (SP) has been proved for the existing sensors technologies without using sensor power enhancements or external power sources and the coverage radius may extend to several tenses of kilometers. SP is an aerial platform that operates in a quasi-stationary position as defined in Radio Regulations (RR) No. S1.66A as "a station located on an object at an altitude of 20 to 50 km and at a specified, nominal, fixed point relative to the earth" and carrying communications payloads [8-26]. We can further improve the link performance of the SP-WSN by configuring the antennas at the SP and optimizing it for maximum performance improvement. The antennas used for SP communications include fixed spot beam antennas or adaptive antenna arrays, therefore in this paper, the two antenna types are examined and the antenna array in the form of concentric circular arrays is optimized to improve the SP-WSN communication performance.

The paper is arranged as follows; section II describes the structure of the SP-WSN and section III provides the communications link equation used for evaluating the performance of SP-WSN. Section IV proposes the adaptive antenna technique for SP-WSN coverage as well as the conventional antenna and section V provides simulation results for both the conventional antenna and the proposed antenna array technique. Finally section VI concludes the paper.

II. STRUCTURE OF SP - WSN

SP is an aerial station that is capable to provide a variety of communications applications, monitoring, surveillance, and even in noncommercial military applications. Recently, the SP provides a good candidate for WSN which may be used in many scenarios. In this paper the SP acts as a global sink station that collects the ground sensors data either from a large area or in a cellular fashion as shown in Fig. 1. The use of SP as a sink station provides not only a large area coverage, but also a security on the sink itself as it is highly elevated. In addition, the SP acts as a global sink station that can provide coverage up to 1000 km diameter when located at 20 km altitude. The structure shown in Fig. 1 can be modified to include sub-sink stations on ground which collects data from nearby sensor nodes and forward it to the global SP sink. This configuration is suitable for cellular WSN but on the other hand is not secure enough as the sub-sinks are located on the ground. The other proposed scheme is direct transmission from ground sensor nodes to the global SP sink which will be proved in this paper using the same sensor technology and without the need to increase either the transmitted power from them or the transmitting antennas.

In the following section, we will describe the SP-WSN link equation that will be useful in evaluating the system performance.

III. LINK EQUATIONS AND SYSTEM EVALUATION FOR SP - WSN

The quality of link between a SP sink and the ground sensors depends on the environment where the sensors exist, the elevation angle between the SP and the sensors or the breadth of the coverage, transmitting frequency, bit rate and the distance of the link. Additional link parameters also apply such as the transmitting power, transmit and receive antenna gains and the atmospheric conditions. To evaluate the system performance we can rely on the bit energy-to-noise power spectral density which is a main parameter affecting the probability of error in the system according to the modulation scheme applied. To determine this ration we may first define the received power at the SP sensor as follows:

$$P_r = P_t G_s G_H / P_L \qquad (1)$$

where P_t is the sensor transmitting power, G_s is the sensor antenna gain, G_H is the SP antenna gain and P_L is the propagation loss between the sensors and the SP.

The last equation may be expressed in dB as:

$$P_r[dB] = P_t[dB] + G_s[dB] + G_H[dB] - P_L[dB] \qquad (2)$$

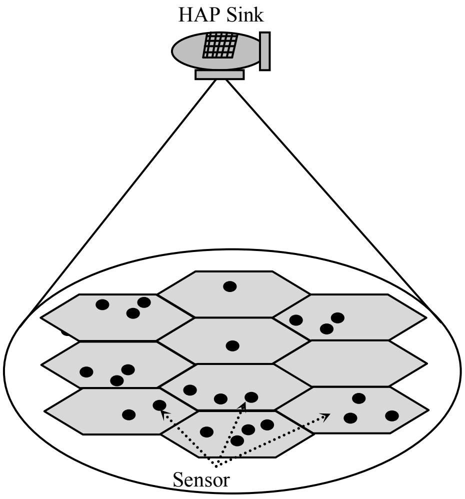

Fig. 1. SP-WSN structure

The propagation loss includes both the loss due to the distance and the loss due to shadowing effect:

$$P_L(\mathrm{d})\ [\mathrm{dB}] = P_L(\mathrm{do})\ [\mathrm{dB}] + 10n\log(d/d_o) + X_q \qquad (3)$$

where n is the pathloss exponent, d_o is a reference distance and d in the separation distance between SP sink and sensor node.

The propagation loss $P_L(d_o)$ in dB is calculated from the following equation:

$$P_L(d_o) = 20 \log (4\, \pi\, d/\lambda) \qquad (4)$$

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

The value of n and sigma depend on the propagation environment where for free space propagation $n = 2$ and a typical value of sigma in SP – WSN is 2 dB.

The received power at the SP sink is not the only key parameter as a performance measure but another very important quantity denoted as the ration of the bit energy to noise spectral density (E_b/N_o) which determines with the modulation scheme the probability of bit error. This ration is given by:

$$E_b/N_o\,(x,y) = P_t A_s\, A_H / N_o\, R_b\, P_L \qquad (5)$$

where R_b is the bit rate and (x,y) is the location of the sensor node as shown in Fig. 2 which determines the distance d from the following relation:

$$d = \sqrt{x^2 + y^2 + z^2} \qquad (6)$$

The $E_b/N_o\,(x,y)$ may be expressed in dB as follows:

$$E_b/N_o\ [\mathrm{dB}] = P_t\ [\mathrm{dB}] + G_s\ [\mathrm{dB}] + G_H\ [\mathrm{dB}] - P_L\ [\mathrm{dB}] - N_o\ [\mathrm{dB}] - R_b\ [\mathrm{dB}] \qquad (7)$$

As shown from (5) and (7), E_b/N_o can be improved by increasing the antenna gain either in the transmitting sensor node or at the SP sink. Increasing antenna gain at the sensor node is physically very difficult due to the increased antenna size and hence the overall sensor volume which in many cases is undesirable. At the SP sink, the large size and power make it possible to deploy large antennas or antenna arrays which can be optimized to improve the quality of link in SP – WSN as will be discussed in the next section.

IV. THE PROPOSED CONCENTRIC CIRCULAR ARRAYS TECHNIQUE FOR SP SINK COVERAGE

In this section, the array configuration and the proposed beamforming technique at the SP sink will be demonstrated. There are a variety of antenna arrays for beamforming applications such as the planar two-dimensional array, circular arrays and the concentric circular arrays (CCA). The last array configuration has interested features such as the capability of symmetrical beamforming in all azimuth range (i.e. 360 degrees beamforming) with reduced sidelobe levels [27-42]. Therefore, in this paper we will use this array configuration to provide both gain and beamwidth requirements.

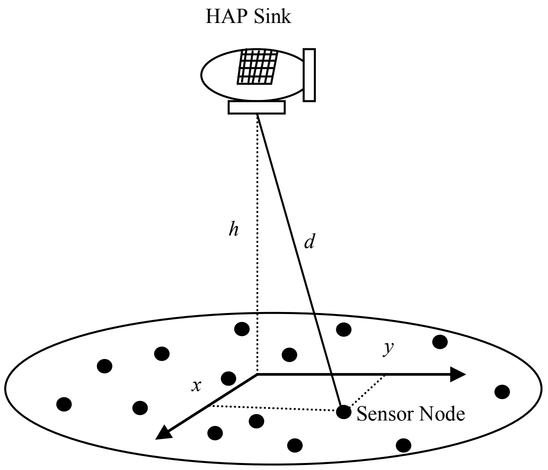

Fig. 2. SP-WSN sensor coordinates and link distances

Assuming that we have *M* rings CCA, and then we design a *one-dimensional array* of *2M* elements of a certain sidelobe level R_o and obtain the array coefficients from the following design steps:

1- Find the value of z_o from the following equation:

$$z_o = 0.5\left(\left(R_o + \sqrt{R_o^2 - 1}\right)^{1/p} + \left(R_o - \sqrt{R_o^2 - 1}\right)^{1/p}\right) \qquad (8)$$

where R_o in this equation is in ratio and $p = 2M - 1$

2- The normalized amplitude coefficient of the m^{th} element in the one-dimensional Dolph-Chebyshev array is calculated as:

$$\chi_m = \frac{\sum\limits_{q=m}^{M} (-1)^{M-q} z_o^{\,2q-1} \dfrac{(q+M-2)!(2M-1)}{(q-m)!(q+m-1)!(M-q)!}}{\sum\limits_{q=1}^{M} (-1)^{M-q} z_o^{\,2q-1} \dfrac{(q+M-2)!(2M-1)}{(q-1)!(q+m-1)!(M-q)!}}, \qquad (9)$$

where $m = 1, 2, ..., M$

3- Finally, the CCA ring coefficients will be given by:

$$w_m = \left(\frac{\sum\limits_{i=1}^{M} N_i}{\sum\limits_{i=1}^{M} \chi_i N_i}\right) \chi_m \qquad (10)$$

The resulted sidelobe level of the CCA using (10) provides sidelobe levels that are different from R_o due to the change in the array configuration, but actually when we vary the value of R_o the sidelobe levels of the weighted CCA vary and the sidelobe levels reaches a floor at R_o= 80 dB as demonstrated in [8]. The main purpose here is to provide the required coverage radius by optimizing the array weights, the interelement spacing distances, innermost ring size and the number of rings. The cell boundary can be defined by several limits such as the 3 dB or 10 dB power contour. We will apply the 10 dB contour as the cell boundary as in [23] for the purpose of comparison. The antenna model developed by [29] was adopted where the directivity pattern of the aperture antenna was modeled by:

$$D(\theta) = (\cos(\theta))^n \frac{32 \log(2)}{2\left(2 \cos\left(\sqrt[n]{0.5}\right)\right)^2} \qquad (11)$$

Therefore, optimizing this function to find the value of *n* will provide a good approximation to the real radiation pattern. The power pattern in (19) is designed for two types of cells; a 30 km radius and another smaller cell of 8 km to examine wide coverage and possibility of cellular coverage respectively. The power gain profile for the two cases is shown in Fig. 3 where the first corresponds to the 8 km cell and the lower curve corresponds to the conventional spot-beam antenna design as in (19) while the second upper curve is for the proposed optimized CCA that gives the same power profile but at much higher boresight gain.
In addition, Fig. 4 provides the power gain profile for the two antenna types designed for 30 km SP cell. In this figure, the optimized CCA provides an increased higher boresight gain by about 17 dB which is an incredible amount of power gain difference and should reflect an improvement in the SP-WSN performance.

V. SIMULATIONS RESULTS

In this section, four case studies are examined to show the feasibility of the proposed optimized CCA technique compared to the conventional spot-beam antenna. The comparison is based on the E_b/N_o as a performance measure of the SP-WSN. The sensor nodes are chosen with the same existing technology. The operating frequency is chosen in the free industrial, scientific and medical (ISM) band. We consider here for comparison the 868 MHz frequency and the transmitting bit rates is 38.4 kb/s. The modulation scheme is the binary phase shift keying (BPSK). In the first case, as shown in Fig. 5, the cell radius is 8 km, the transmitting frequency is 868 kHz and R_b is 38.4 kb/s. The two antenna cases show a possible and feasible link between the SP sink and the ground sensor nodes. In this case, the optimized CCA shows a better link performance by about 10 dB due to the improved antenna gain.
The second case is described for the 30 km cells and the performance comparison is shown in Fig. 6 where it is possible for establishing the network in this case with improved performance for the optimized CCA. Therefore, in all examined cases, the optimized CCA provides better performance and feasible link between the SP sink and the ground sensor nodes although the very long distances separating them.

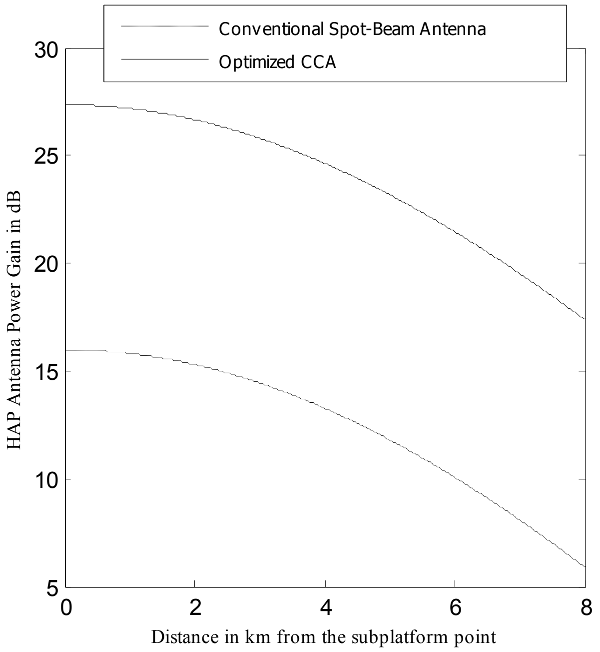

Fig. 3. Antenna power gain of conventional spot-beam antenna and optimized CCA for 8 km SP cell.

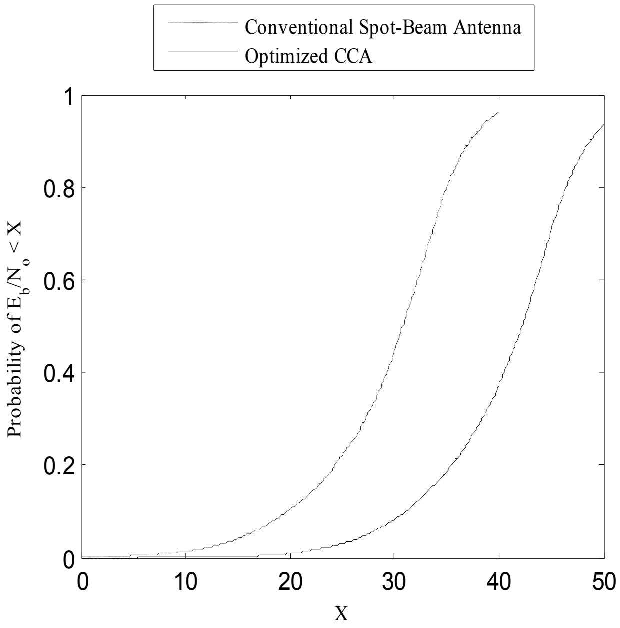

Fig. 5. Probability of E_b/N_o for the two antenna types designed for 8 km cell at 868 MHz and R_b = 38.4 *kb/s*.

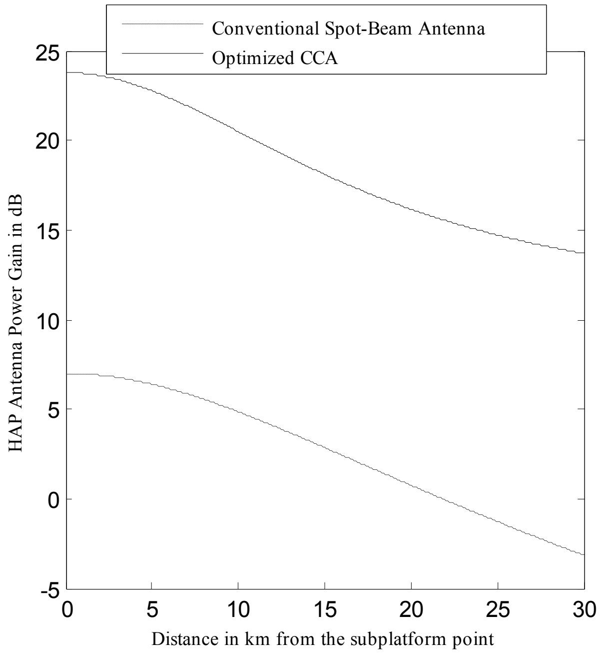

Fig. 4. Antenna power gain of conventional spot-beam antenna and optimized CCA for 30 km SP cell.

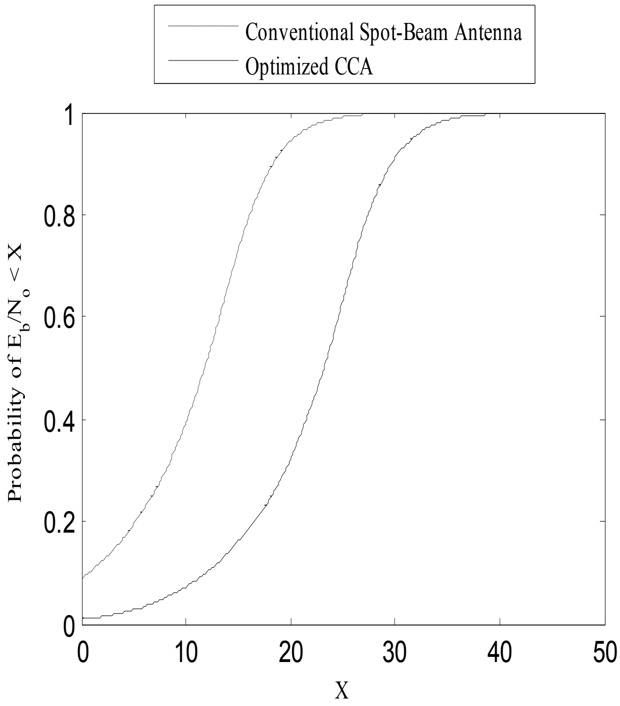

Fig. 6. Probability of E_b/N_o for the two antenna types designed for 30 km cell at 868 MHz and R_b = 38.4 *kb/s*.

VI. CONCLUSIONS

In this paper, the wireless sensor network has been built using the ambitious technology of high-altitude platforms. The proposed SP-WSN scenario provides many advantages over the conventional terrestrial or satellite WSN such as the wide coverage and good quality of communications link. The performance of this system can be improved by improving the quality of link between the sink and the sensor nodes using concentric circular arrays. The array is used at the SP and is optimized to provide better gain and coverage over the required area. The optimization process also minimizes the out-of-coverage radiation which is important for cellular WSN. Compared with the conventional spot-beam antenna techniques, the proposed CCA technique improves the communication between SP and sensor nodes than using the conventional antenna techniques as depicted by simulation results.

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