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

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ABSTRACT
In this paper, the performance of Wireless Sensor Networks (WSN) is improved using adaptive antenna technique and High-Altitude Platforms Systems (HAP). An adaptive concentric circular array (ACCA) is proposed to improve the communications link between sink and sensor nodes. The system is first demonstrated for several scenarios including different cell sizes at a HAP height of 20 km and the quality of link in terms of the ratio of bit energy to noise power is demonstrated where it shows the capability and reliability of building HAP-WSN despite of the long distance between ground sensors and HAP sink. The proposed ACCA technique provides a power gain profile that both increases the power to and from sensor nodes as well as it reduces the out-of cell radiation to other HAP-WSN areas.

Keywords
HAP, WSN, Adaptive Antenna, Concentric Circular Arrays

1. INTRODUCTION
The huge advances in wireless communications technologies have aided other related systems to gain more interest and provide several innovative services. Recently, Wireless Sensor Network (WSN) has gained attention where it is applied in many applications including vital industrial manufacturing techniques, monitoring in military applications, agriculture and fluid detection, and in several security issues [1-4]. This network contains a number of remote sensors that measure the physical quantities and forward its data to a central point called sink station. For ground WSN systems, the distance between sensors and sink points depends on the communication environment where the power exponent is almost around 4. The other main parameter in WSN is the power source available for sensors which usually comes from batteries and forms a very limitation to the system lifetime. Another main issue regarding WSN is the extension of radio coverage which depends on the communication technique applied between these sensor nodes and sinks and the antenna will play an important parameter for both sensors and sink power drains reduction. The ground-based WSN has a very limited communication range due to the channel impairments including multipath fading problems. The existing ground based WSN has limited its cell coverage to few meters due to the limited battery life time at sensors. The coverage range and battery life time can be extended by switching to a different type of propagation channel to reduce the multipath fading problem namely using the free-space or line-of-sight communications. This kind of propagation channels can be obtained by applying satellite communications or simply using very high sink station that may be located on a very high mast or tower. Recently, an efficient and reliable communication system based on the High-Altitude Platform (HAP) [5-8] has gained interest in research for WSN and has been proved for the existing sensors technologies without using extra sensor power while the coverage radius may extend to several tenses of kilometers. HAP is an aerial platform that operates in a quasi-stationary position in the stratospheric layer at altitudes ranging from 20-50 km high and carrying communications payloads [9-16]. The communication link performance of the HAPWSN can be improved by configuring the antennas at the HAP where the antenna technology plays a very important rule [17-28].

The paper is arranged as follows; section 2 describes the HAPWSN system configuration and section 3 provides the communications link equations that describe HAPWSN. Section 4 proposes the adaptive antenna technique for HAPWSN coverage as well as the conventional antenna and section 5 provides simulation results for both the conventional antenna and the proposed antenna array technique. Finally section 6 concludes the paper.

2. HAPWSN CONFIGURATION
HAP is an aerial station that is capable to provide a variety of communications applications, monitoring, surveillance, and even in noncommercial military applications. Recently, the HAP provides a good candidate for WSN which may be used in many scenarios. In this paper the HAP 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 HAP 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 HAP 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 HAP 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 HAP 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 HAP-WSN link equation that will be useful in evaluating the system performance.

3. LINK BUDJET FOR HAPWSN

The quality of link between a HAP sink and the ground sensors depends on the environment where the sensors exist, the elevation angle between the HAP and the sensors or the breadth of the coverage, transmitting frequency, bit rate and the distance of the link [4]. 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 HAP sensor as follows:

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

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

The last equation may be expressed in dB as:

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

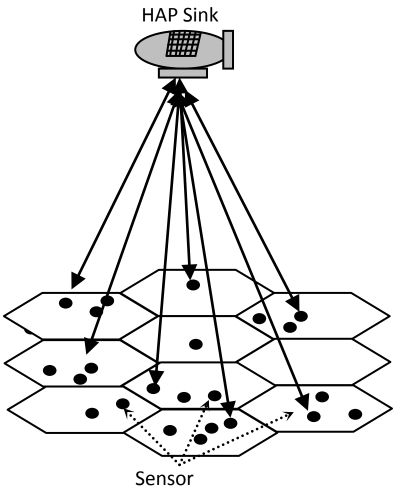

Fig. 1: Cellular HAPWSN

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

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

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

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

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

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 HAPWSN 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:

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

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

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

An example for the coverage of a single HAP at 20 km high over Taif City, KSA, is depicted in Fig. 2(b) where the whole city can be viewed with very good and high elevation angles that ensure almost line-of-sight propagation scenario. The $E_b/N_o\,(x,y)$ may be expressed in dB as follows:

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

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 a HAP 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 HAP 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 HAPWSN as will be discussed in the next section.

4. ACCA FOR HAPWSN

In this section, the array configuration and the proposed beamforming technique at the HAP sink will be demonstrated. There are a variety of antenna arrays for beamforming applications such as the planar two-dimensional array, circular arrays and adaptive concentric circular arrays (ACCA) [29-42]. 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. In [29-31], the tapered beamforming is applied for ACCA and has proved good performance especially in the sidelobe reduction. The design of flattop ring cells is also demonstrated in [32] where the ACCA is applied using Hamming windows. Other ACCA techniques can be also applied for HAP communications as in [33-42], therefore, in this paper we will use this array configuration to provide both gain and beamwidth requirements.

Assuming that we have M rings ACCA, 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:

Find the value of z_o from the following equation:

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

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

The normalized amplitude coefficient of the m^{th} element in the one-dimensional Dolph-Chebyshev array is calculated as [42]:

$$\chi_m = \frac{\sum_{q=m}^{M} (-1)^{M-q} z_o^{2q-1} \frac{(q+M-2)!(2M-1)}{(q-m)!(q+m-1)!(M-q)!}}{\sum_{q=1}^{M} (-1)^{M-q} z_o^{2q-1} \frac{(q+M-2)!(2M-1)}{(q-1)!(q+m-1)!(M-q)!}}, \quad (9)$$

where $m = 1, 2, \ldots, M$

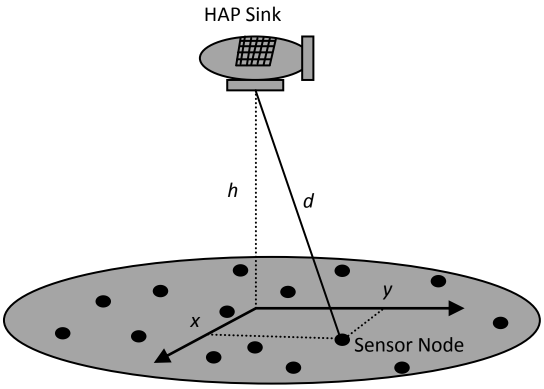

Fig. 2(a): HAPWSN sensor coordinates and link distances.

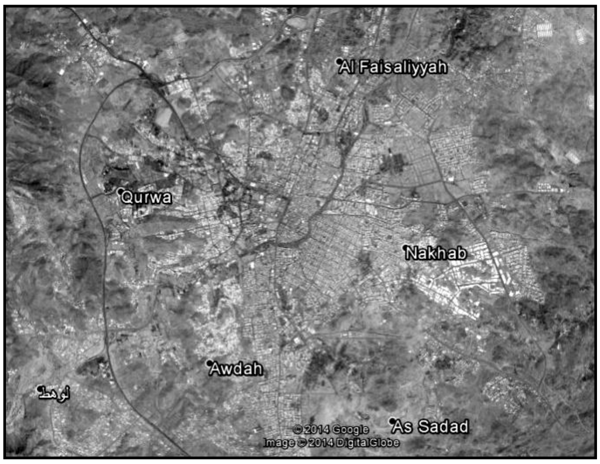

Fig. 2(b): HAP view at 20 km high over Taif City, KSA.

Finally, the CCA ring coefficients will be given by:

$$w_m = \left(\frac{\sum_{i=1}^{M} N_i}{\sum_{i=1}^{M} \chi_i N_i} \right) \chi_m \quad (10)$$

The resulted sidelobe level of the ACCA 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 ACCA vary and the sidelobe levels reaches a floor at R_o = 80 dB as demonstrated in [42]. 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 [18] was adopted where the directivity pattern of the aperture antenna was modeled by:

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

Therefore, optimizing this function to find the value of n will provide a good approximation to the real radiation pattern. The power pattern in (18) 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 (18) while the second upper curve is for the proposed optimized ACCA 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 HAP cell. In this figure, the optimized ACCA 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 HAP-WSN performance.

5. SIMULATIONS RESULTS

In this section, four case studies are examined to show the feasibility of the proposed optimized ACCA technique compared to the conventional spot-beam antenna. The comparison is based on the E_b/N_o as a performance measure of the HAPWSN. 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 rate 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 HAP sink and the ground sensor nodes. In this case, the optimized ACCA 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 ACCA. Therefore, in all examined cases, the optimized ACCA provides better performance and feasible link between the HAP sink and the ground sensor nodes although the very long distances separating them.

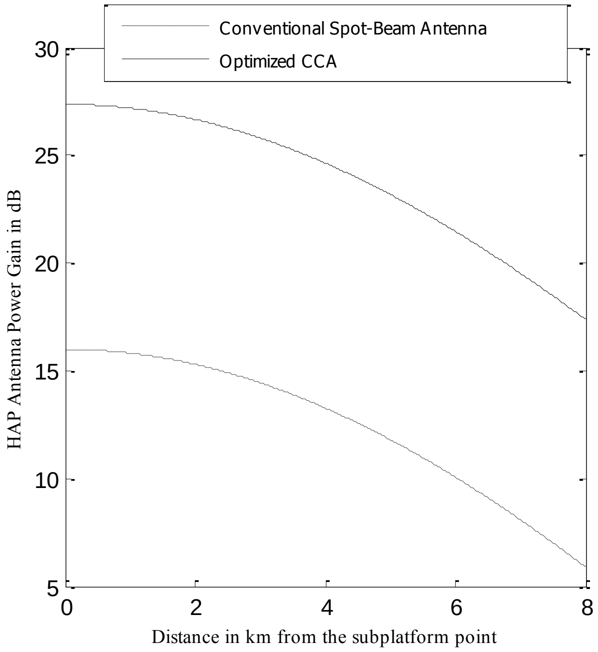

Fig. 3: Gain of conventional antenna and proposed ACCA designed for 8 km HAP cell.

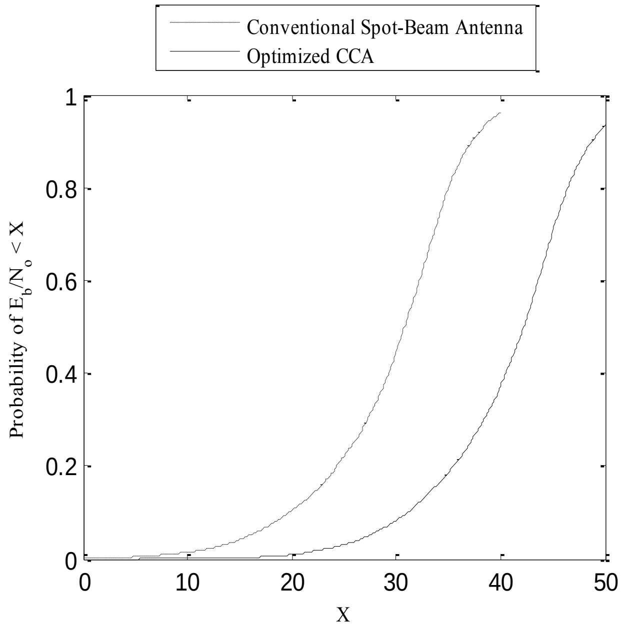

Fig. 5: Eb/No for the two antenna types designed for 8 km cell at 868 MHz and Rb = 38.4 kb/s.

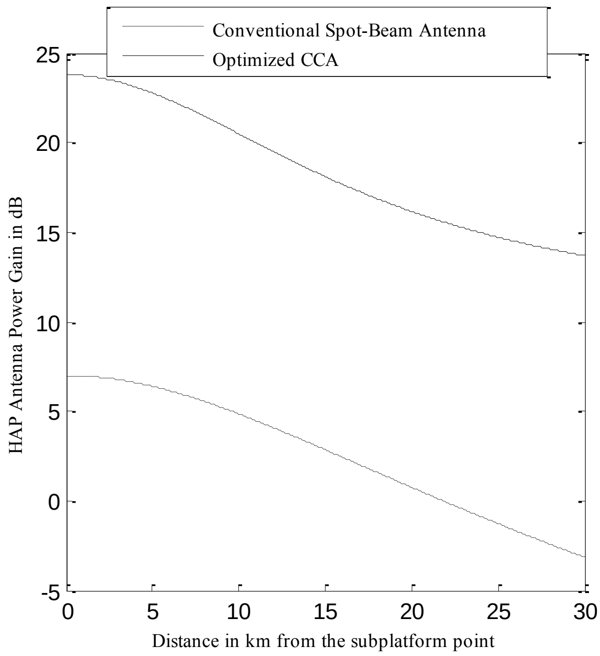

Fig. 4: Gain of conventional antenna and proposed ACCA designed for 30 km HAP cell.

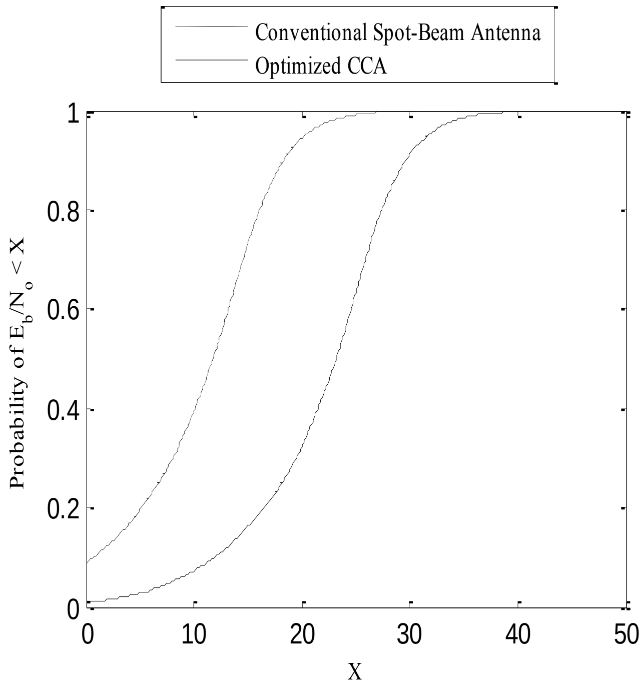

Fig. 6: Eb/No for the two antenna types designed for 30 km cell at 868 MHz and Rb = 38.4 kb/s.

6. CONCLUSIONS

An efficient WSN based on HAP and adaptive antenna array in the form of ACCA has been demonstrated where the HAP forms a central sink station for collecting nodes data on the ground. The proposed HAPWSN system has provided many advantages over conventional terrestrial or satellite WSN including wide area coverage and superior communications performance by improving the quality of link between the sink and the sensors on the ground. The array is used at the HAP and is optimized to provide better gain and coverage over the required area. The main objective is to minimize the out-of-coverage radiation which is important for frequency reuse cellular WSN.

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