Optical Wireless Communication and Recharging Mechanism of Wireless Sensor Network by Using CCRs

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Abstract

Broad spectrum of optical wireless communication is available, which can fulfill the requirements of high speed wireless communication. This is the basic advantage of optical wireless communication over conventional wireless communication technologies. The other important thing is the day by day decreasing size of wireless sensors with the advent of advancement in device processing technologies like micro- and nano-electromechanical systems. This decrease in dimensions of sensors causes serious problem for battery storage capacity. We address this issue and propose a model of communication and recharging of Wireless Sensor Network (WSN) nodes simultaneously using passive optical communication. We propose both Line-of-Sight and Quasi-diffuse communication for this purpose. There are some situations where direct LOS is better option while at non-line-of-sight, the energy of a multi-spot Quasi-diffuse beam can be utilized. In our model we have used modified Corner Cube Retroreflector (CCR) and a newly proposed device Thinfilm Corner Cube Retroreflector (TCCR) for passive communication and recharging sensor nodes. These devices have large angle of diversity due to which they can provide communication facility to large areas. Our analysis shows that the proposed model could show better performance and significant increase in network life time.

Keywords: *Free Space Optics (FSO), Wireless Sensor Network (WSN), Corner Cube Retroreflector (CCR), Thinfilm Corner Cube Retroreflector (TCCR).*

1. Introduction

WSNs have been extensively researched during recent years helping in diverse deployment of sensor networks in various systems and applications. One of the key challenges that precludes the sustained operation of these networks is their limited energy resources. As technology has advanced, the size and cost of these nodes has reduced, making their effective power supply capability more limited. In some application scenarios, the replenishment of power resources might be impossible, altogether. Therefore, a great deal of focus has been given to the long lasting batteries for a sensor node which in result corresponds to enhancements of node and network lifetimes [1].

Replacing batteries in every device at regular intervals of time is one option (such as planned replacement once every year or two) but an extremely expensive one [2]. Special attention must be given to the unattended operations of sensor nodes because the life time of the deployed network is dependent upon the nodes, which if exhausted, can exhibit shortened life time of the entire network [3].

Another way to extend the lifetime of a WSN is through load balancing, such that all the sensors deplete their energy as slowly and uniformly as possible. Also, the behavior of the sink has an impact on the network lifetime. Indeed, sensors in
the proximity of a static sink act as data aggregators since most of the data passes through them. Sensors near a static sink would suffer from a severe depletion of battery, which may result in possible network disconnection and disruption of the data reaching the sink [5]. One possible way to resolve such network portioning might come from clustering [6]. While all of these conservation schemes slow down the battery drainage process considerably, it is only possible through battery replenishments of partial or whole networks that ensure their sustainability for extremely long time periods.
A feasible approach is to utilize the presence of heterogeneous nodes (i.e., nodes with an enhanced energy capacity or communication capability) in a sensor network in order to increase network reliability and lifetime. The nodes which are wire-able (or mobile) may scavenge and harvest energy, on whenever and wherever need arises. However, there remains the challenge to analyze and determine the type of heterogeneous nodes and the topology in which they should be deployed [4].

While sensor nodes and networks are attributed primarily in the Radio Frequency (RF) domain, optical wireless communication support for sensory equipment and data demonstrates distinct advantages over other wireless systems, mainly due to the high achievable data rates and low power consumption requirements—especially due to the very-small-size and light weight components [7]. Optical wireless links provide greater promises for secure, extremely high data rate communication between fixed or mobile nodes due to their inherent properties such as directivity and narrow beam [8]. One of the applications of such devices is the use of passive transmitters such as a corner cube retro-reflector (CCR) in Smart Dust Project [18]. Its small size, ease of operation, and low power consumption can be of great significance as its usage is proposed for wireless sensor networks [9].

The wirelessly recharging mechanisms have been used in difficult, harsh or totally inaccessible environments, where battery replacement is impossible or at least a costly task, e.g., in mines, underwater, in space, and between portable phones. In early days of development in electromagnetism, before wire-grid developments, serious efforts were devoted to wirelessly recharging battery over long distances. There were reports of little success and therefore the efforts were deprived of serious attention. In the last two decades, research efforts have been made to develop battery recharge mechanism over short $L_{trans} << L_{dev}$ (where L_{trans} is wirelessly recharging range and L_{dev} is device dimension) and mid-range distances $L_{trans} >> L_{dev}$. A new mechanism for recharging by using strong-coupled resonant technique by using electromagnetism at mid-ranged was proposed by Aristeid et at [13]. A mobile and a static WSN node were recharged by using electromagnetic induction through mobile robots [10, 11]. Another way to recharge the sensor node batteries is harvesting a microwave RF source, by using directional antennas. It is specially designed for point, listen and see (PLS) systems, which are mounted at height. Users avail this service by pointing their IR enabled mobile or PDA towards it [12]. Micro Electro Mechanical Systems (MEMS) devices of micro- and nano-metric scales are required to be provisioned with extremely small size batteries. Therefore, no matter how efficiently or austerely the batteries are utilized, the conservation schemes deem insufficient. We therefore, have to consider efficient recharging mechanisms, which are effective over medium to longer distances.

In this paper, we adopt this strategy to devise a model that optically recharges RF sensor nodes equipped with the recharging facility. The rest of the article is organized as follows. In section II, we present the node and network model and describe the architectures of CCRs and TCCRs. The mathematical model of the proposed mechanism is also elaborated. Recharging of wireless sensor network backbone nodes and *on-demand* recharging as a partial network recharging scenario are presented in section III. Finally section IV concludes the paper and discusses possible future work.

2. Optical Wireless Sensors Recharging

This model describes the entities and their interplay for wireless optical communication and recharging sensor node using an IR- laser. We ignore the details of optical losses occurring due to scattering and absorption of light in the free space to keep the model tractable. We assume that the network is established in such a way that a large number of small wireless nodes (as shown in Fig. 1) are randomly deployed and they communicate using radio frequency. A clique of small nodes can communicate with the head node, hereafter termed as the main node. These nodes are resource rich nodes, having all standard components of a typical RF node, and also containing optical components.

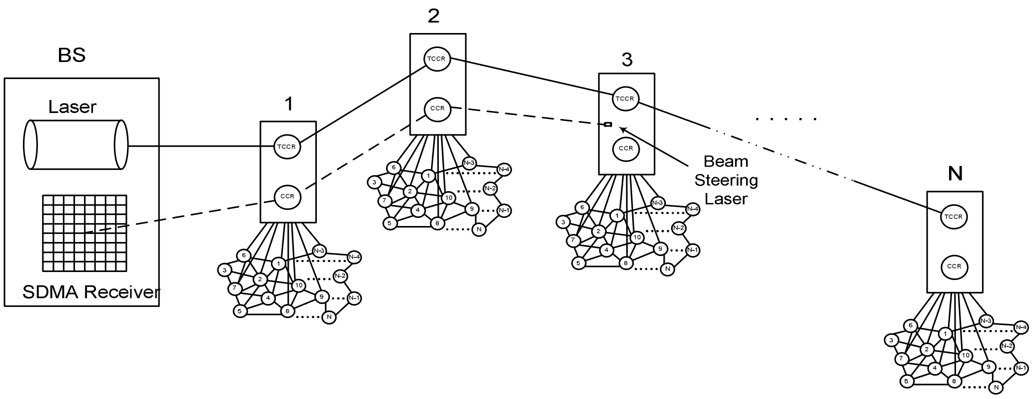

Figure 1. Laser recharged wireless sensor network

In the model, the main nodes as shown in Fig.1 communicate with the Base Station (BS) using their beam steering lasers, either directly when in the Line of Sight (LoS), or indirectly through other main nodes using CCRs. BS has complete information of location coordinates of all main nodes.

The main nodes in region of interest (ROI) are deployed in such a manner that these nodes form a wireless optical backbone. BS communicates directly with the main nodes using CCRs when in LoS or indirectly through other main nodes. Since every main node may be communicating with numerous nodes within a clique, its battery would run out rapidly as compared to the small nodes, essentially partially or completely tearing down the network backbone. In this paper, we present a recharge mechanism for such juncture nodes through the incorporation of corner cube retroreflector (CCR) and its variant TCCR. The CCR as proposed by J. M. Kahn and K. Pister et. al [14], [15] is used for distance sensing as well as for FSO passive communication in small optical sensors. However it has not been designed for recharging of the sensor nodes.

Wireless sensor Network (WSN) could be built by employing a passive optical device known as the corner cube retro-reflector (CCR). CCR consists of three high reflecting mirrors placed orthogonally to each other. By misaligning one mirror of the CCR, a sensor node can modulate a signal. It could act as Modulating Corner Cube Retroreflector. It utilized BS transmitted optical power passively for modulating the incoming signal. It could absorb energy for its own circuitry. When used to modulate an interrogating beam from the base station, the CCR yields huge energy savings compared to active laser communication [9, 15, 17].

CCR communication is passive and bidirectional between a node and the base station, and is especially attractive because all the optical energy for communication is supplied by the base station, a small fraction of energy used for the modulating circuitry of the CCR on the node. CCRs are very appropriate for WSNs due to their small size, ease of operation and negligible power consumption. All the main nodes of WSN are equipped with CCR's as shown in Fig.1. Those nodes within LOS of base station oriented their CCRs towards BS, while all others oriented towards closest neighboring nodes so that they communicate with BS Quasi-diffusively (passively) through main nodes as shown in Fig. 1. Optical communication based on retro-reflector technology brings many advantages. It reduces size and mass of the communication payload for each sensor because it does not need to carry its power sources and active laser. Furthermore the pointing requirement on both end of the link is more relaxed than conventional free space optical link, simplifying network self-organization and medium access control. Network architecture designed to take advantage of the space-division, optical retro-reflector technology to provides energy efficient uni-cast and multi-cast. When a node wishes to retrieve information from another node, it transmits an un-modulated laser beam (referred to as an interrogation beam) toward that node. The interrogation beam is used to confirm the identification of node and start the transmission of data and to supply the necessary optical power for the return signal. When a node has information to communicate and detect the interrogation beam, it will activate its MRR**,** which converts the un-modulated signal into a modulated optical signal and returns it to the SDMA receiver.

The strength of wireless sensor network lies in life and efficiency of backbone. One of the main targets is to minimize consumption of intrinsic battery energy of these backbone (main) sensor nodes and recharging using highly asymmetric CCR links. The passive transmitters heavily depend upon the resources and capabilities of the BS transceivers to minimize the need for an active laser, power supply and the associated pointing mechanism. Modulating CRR components can be very small and operate at extremely low power level, which helps enhance the operational lifetime of the sensor network. Two examples of such low power miniature systems are the MEMS mirror and the Multiple Quantum Well (MQW) modulators [9, 17]. The typical field of view of CCR device can be as large as several ten's of degrees. Using an array of CCRs, a very large field of view can be achieved. The pointing requirement of modulating CCRs is high and therefore Quasi-diffusive links can be developed.

Now we assume that D is the diameter of spot made by BS laser at the surface of TCCR at distance r and θ is the angle as shown in fig. 2.

$$D/2 = r\tan\theta \qquad (1)$$

$$I_r = \frac{P_r}{\pi(D/2)^2} \qquad (2)$$

$$P_r = P_{cap} \quad (3)$$

P_{cap} is power captured by TCCR

$$P_{abs} = P_{cap} * \alpha \quad (4)$$

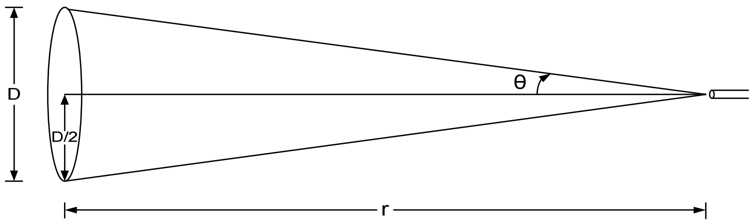

Figure 2. T_x beam cone spot having diameter D at distance r

Where irradiance and power at distance r are represented by I_r and P_r respectively. Absorption α according to Beer-Lambert Law

$$\alpha = \frac{4\pi k}{\lambda} \quad (5)$$

$$P_{ref} = P_r - P_{abs} \quad (6)$$

P_{ref} and P_{abs} are reflected and absorbed power respectively.

$$P_{cap\_mis} = P_{cap} Cos\theta_c \quad (7)$$

P_{cap_mis}, and θ_c shows power capture by TCCR in case of one misaligned mirror, angle between effective area and incident ray.

Mirror 'A' of CCR and TCCR is orthogonally fixed with respect to horizontal plane, while 'B' permanently subtends an angle (90^o + φ) with mirror 'A' (where φ is a positive very small angle), and mirror 'C' is loosely bound which can be tilted by applying electrostatic force. The purpose of giving tilt to mirror 'B' is to increase the angle of reflection from mirror 'A' as shown in Fig. 3. This will increase the effective area of mirror 'A'. Subsequently, the reflected beam span is maximized increasing its range of coverage. Since the mirror 'C' is loosely bound therefore it can be tilted by applying electrostatic force and returned back to its original position. This allows modulation of incoming beam for communication purposes.

A base station has variable power laser and spatial (space) division multiple access (SDMA) receiver. Big rectangular nodes are main nodes equipped with CCRs and TCCRs. Circular nodes are small nodes having less resources and only few of them are used simultaneously in one clique (or cluster).

We propose a new device, which acts not only as device for recharging battery as well as communication, which gives sensors specially (micro and nano) smart sensors maximum possible battery life. This device is termed as Thin film Corner Cube Retroreflector (TCCR).

In TCCR, we take two mirrors which are oblique at small angle φ to the horizontal plane, such that the area of the sector of the reflected beam from CCRs or other TCCRs could be maximized. One of the mirrors is misaligned and can be tilted by using electrostatic force, and may subsequently come back to its original position by removing the force as shown in Fig. 3 and Fig. 4.

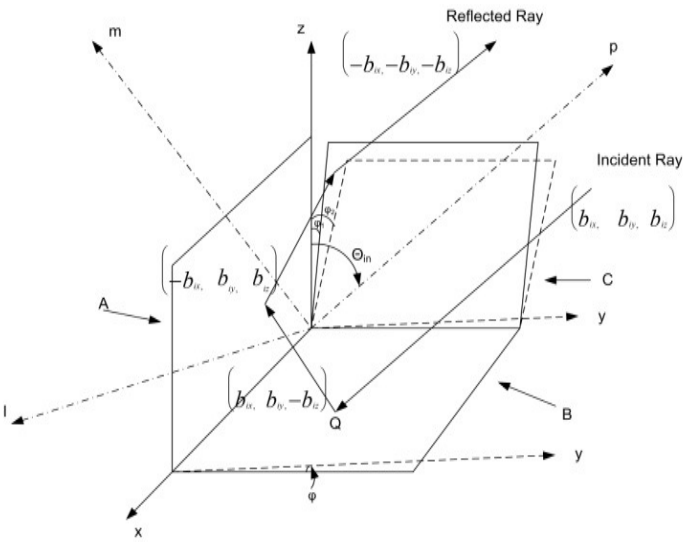

Figure 3. CCR with two mirrors tilted at small angle φ , where incident direction is b_{ix} , b_{iy} , b_{iz}

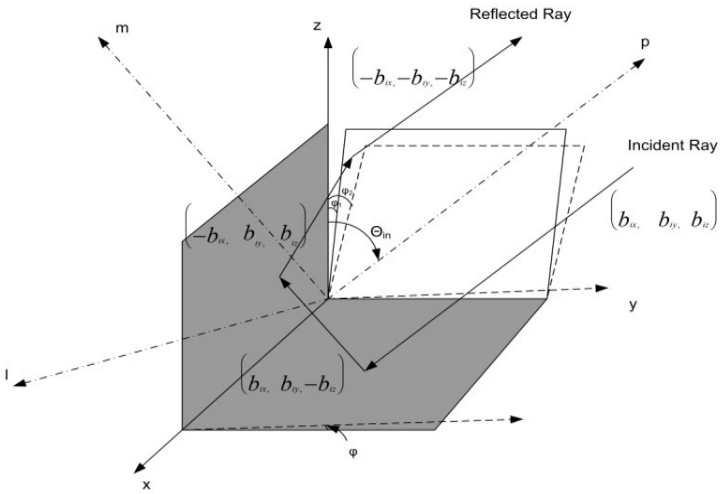

Figure 4. Structure of TCCR

The shaded mirrors are partially reflecting thin film. Thin film is quoted on the back of partially reflecting mirrors, which acts as a rechargeable battery. The light transmitted in partially reflecting mirrors of TCCR is absorbed by the thin film battery [16] and used the absorbed power for recharging. The incident laser beam coming from BS directly, or indirectly through other main nodes' CCRs is incident and pass through only those TCCRs which need to recharge their batteries. The ray tracing of incident and reflected beams are shown in Fig. 3 and Fig. 4 respectively. The incident ray and the reflected rays from plane 'B' are shown by solid directional lines, while the ray coordinates are shown in dotted directional lines. The incident ray has b_{ix}, b_{iy}, b_{iz} , and the reflected ray has $(-bi_x, -b_{iy}, -b_{iz})$ unit vectors.

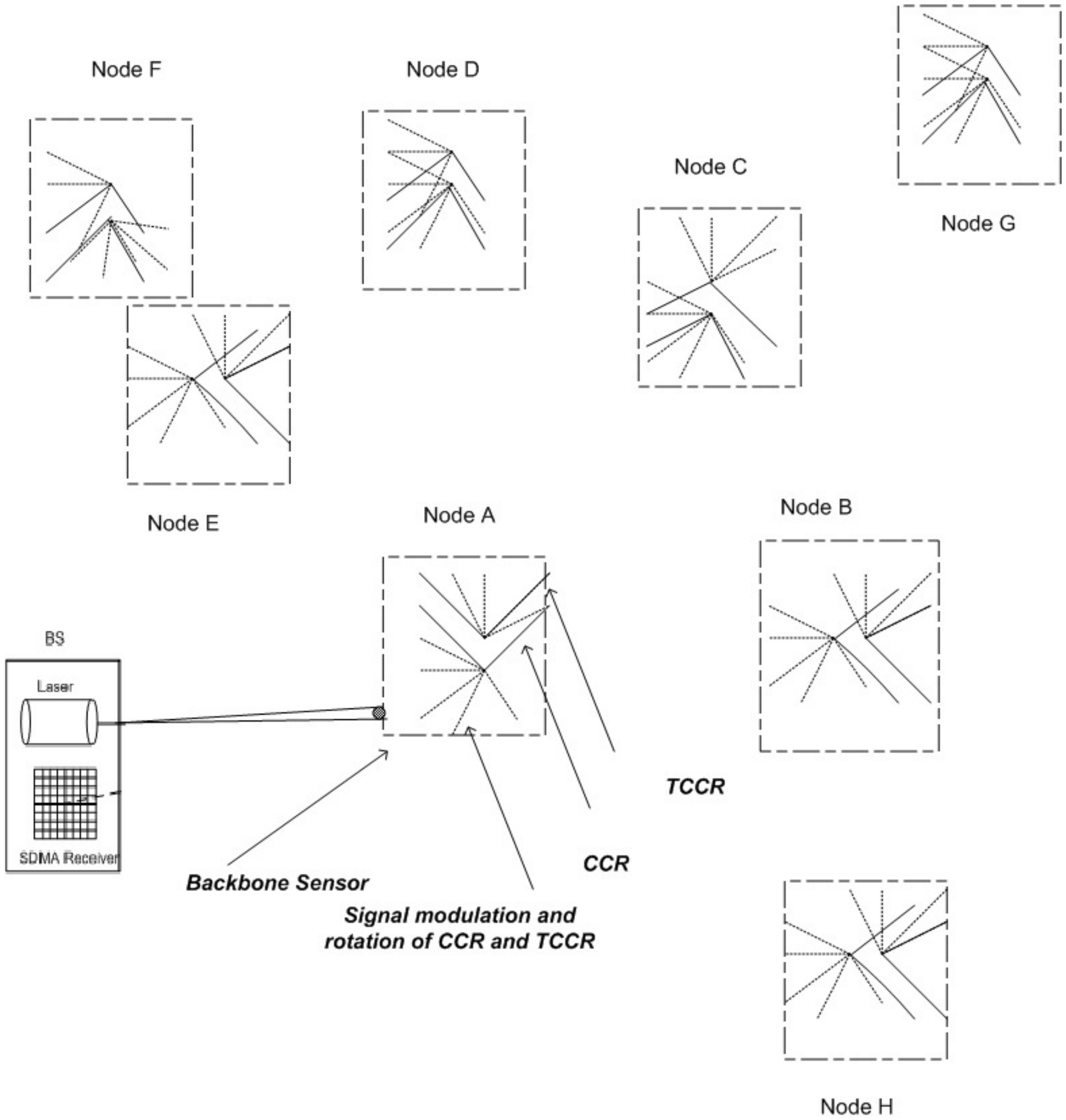

Figure 5. Configuration of backbone nodes CCRs and TCCRs communication

The environmental geometry and the symbolic motion of CCRs and TCCRs is shown in Fig. 5. This tilted motion can modulate as well as redirecting the incoming light towards target sensor(s) or base station. The information that is transmitted in an optical link requires some form of modulation in order to for the signal to be encoded into a physical parameter. This physical parameter is usually the intensity, the frequency, or the polarization of the emitted light. The modulating signal is then demodulated in the receiver to recover the transmitted information. The optical link is based on reflection of infrared diffuse and line of sight laser light, which emit coherent light and it can spread. As laser travel to far from BS and got many reflections from CCRS and TCCRs, therefore the beam may become diffuse or Quasi-diffuse. This configuration becomes complex as three directed LOS, NLOS/diffuse and

Q-diffuse configuration involve in this model. The use of narrow FOV receivers allows optical concentrators to be employed along with thin film optical filters, since the angular dependence of the filter response does not pose a problem. Directed LOS is not effected by multipath propagation, and ambient background light is largely rejected. Thus, the potential data communication rate is limited only by the available power budget [19]. Although, directed LOS links need to be pointed prior to use, and require an uninterrupted line of sight path between the transmitter and receiver, thus making them susceptible to interruption. By their very nature, we can say that they are more suited to point-to-point links rather than point-to-multipoint broadcast type links, thus reducing their flexibility. Directed LOS is the most well known link topology, and has been used for many years in low bit rate, simplex remote control applications for domestic electrical equipment, such as televisions and audio equipment. Additionally, directed LOS is the chosen configuration for IrDA links [20], which offer simple point to point network communication. For nondirected LOS and diffuse links, rather than using a single element detector, significant performance improvements can be achieved using an angle-diversity receiver, which may be implemented in one of two ways. A non-imaging angle-diversity implementation consists of multiple receiving elements that are oriented in a different direction, each element having its own nonimaging concentrator. The main drawback of this approach is that it can lead to an excessively bulky and costly receiver. A more elegant implementation is the imaging angle diversity receiver, it is also called fly-eye receiver, which was proposed in [21]. Angle-diversity receivers can simultaneously achieve a high optical gain and a wide field of view. By exploiting the fact that unwanted signals are generally received from different directions to that of the desired signal, they can significantly reduce the effects of ambient light noise, co-channel interference and multipath distortion. An improvement in the power efficiency of diffuse links can be achieved by replacing the single wide-beam diffuse transmitter with a multi-beam transmitter, sometimes referred to as a quasi-diffuse transmitter, which consists of multiple narrow beams pointing in different directions. The performance of diffuse links using multi-beam transmitters and angle-diversity receivers also discussed in many articles [22-25]. In our model the model we will consider all these scenarios and this hybrid passive communication wireless sensor network can simultaneously get advantages of all these types of optical wireless communication. This also makes the battery energy scavenging so that network life could be making longer.

3. Scheduling the Recharge Mechanism

When the laser power P_t arrives from BS and the power captured by the TCCR at distance r is P_r, the laser beam creates a spot on the surface of TCCR of radius D/2 and θ , as shown in Fig. 3. A small part of the captured power is absorbed by the TCCR by the two thin-film coated, partially reflecting mirrors. The absorbed power is used for recharging the thin film battery of the main node. When the battery of any main node is completely recharged then it send message to BS SDMA receiver, directly if LoS exists or indirectly by using optical signals from the CCRs of neighbors (as every main node has complete information about its neighbors). The reflected power from TCCR surfaces goes towards next main node TCCR, which needs to be recharged.

Using a SDMA receiver, a CCR-based optical system can be channelized to receive signals simultaneously from multiple active or passive transmitter nodes as illustrated in Fig. 1. Usually the receiver is equipped with a pixilated focal matrix plane, where each pixel work as a photodetector. When the interrogation beam covers more than one node that have data to send, two simultaneous streams of modulated signal can be returned from bearings. The receiver optics will focus these signals on different parts of the focal plane. If the angular separation is large enough, the two optical signals will strike two different pixels (photo-detectors), which allow both signals to be decoded independently without interference.

Consider another recharging scenario. If the batteries of one main node or more than one main nodes are depleting below a certain pre-specified threshold, then the corresponding main node sends out a message using its beam steering laser towards the BS directly, if in the line of sight, or otherwise, through CCRs of the intermediary main nodes. The BS completes the identification of the soliciting main nodes, subsequently; the variable power IR laser receives a recharge request through the SDMA receiver, and recognizes the locations of requesting main node(s). The BS calculates the required power for the demanding main nodes. The power of the IR laser is adjusted at the required level. Finally, the recharge of the batteries of the requesting node(s) is carried out as shown in Fig. 1. Such a power budgeting ensures that there is no loss of laser power, and therefore the maximum number of nodes can be recharged with the minimum losses.

Not all rays that strike the CCR could be reflected towards our feasible direction. This depends on the incident direction and the location on the CCR that the ray first makes contact in given geometry. For any incident ray, the effective area on each mirror face where an incident ray would be reflected in our feasible direction would be limited. Here the feasible direction is the direction of main sensor node which needs to be recharged.

The incident ray strike only one of the mirrors when an incident ray is normal to one mirror and it strikes two of the mirrors when it is parallel to one mirror and not normal to either of the other mirrors and any other incident ray strikes all three mirrors. When a beam or ray strikes at the shaded area of one mirror, after reflection it would have high probability to strike to the shaded area of an adjacent mirror. Fig 4 explains this supposition by ray tracing that if a beam or ray strikes within shaded area of mirror 'C', it would most probably after reflection be incident within shaded area of mirror 'A'. So we are interested in the incident angle between plane effective areas of mirrors. We assume that the angle between incident beam and effective area is θ_c as shown in equation (7). A three dimensional relationship is shown graphically in Fig. 6, where θ_c varies. A beam focused on the base mirror of TCCR at θ_c, a portion of power of beam is absorbed by the mirrors while reflecting the remaining beam towards another TCCR or CCR or towards the base station receiver. Fig. 6 shows that at some angles there is more absorption and less reflection while at others the phenomenon is opposite. At small θ_c more power is confined onto orthogonal mirrors and therefore there will be more absorption, in this case less time is required to recharge the sensor node battery. So for large area of sector of communication we use large θ_c and for recharging sensor node battery in short time θ_c should be small. Modulating CCRs and TCCR can be tuned in coherence with these techniques. This mechanism provides reliability and long lasting life for the wireless sensor network.

4. Conclusions and future work

Our model describes communication and recharging mechanism for resource rich backbone nodes (the main nodes) in WSNs using free space optics in such a way that passive communication dominates the network. It is assumed that network is installed in harsh and difficult environments, where human accessibility is difficult and the replacement of the batteries is very costly, if not impossible. Our model presents a vivid mechanism of FSO-based recharging in WSNs as well as minimum intrinsic energy consumption of backbone nodes by using passive corner cubical mirror devices. We use Line-of-sight single spot and nonline-of-sight multispot communication mechanism to give our WSN maximum possible life and reliability. Single spot mechanism work well where Base station Transceiver have direct line of sight otherwise Quasi-diffuse multispot links are established.

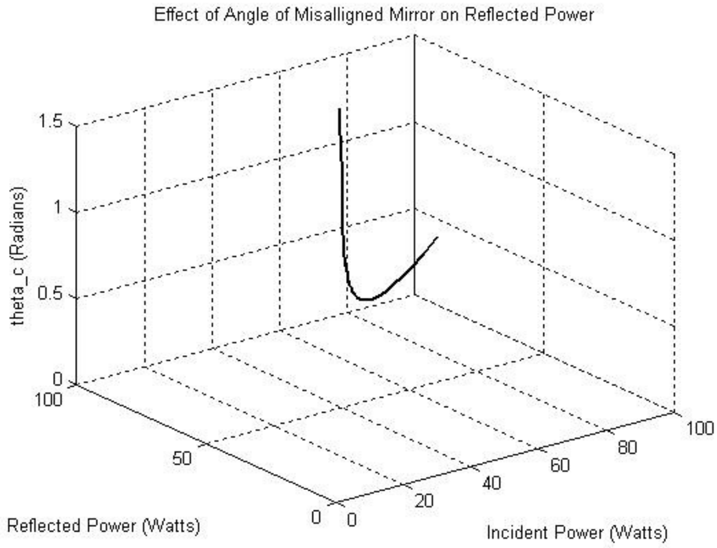

Figure 6. Incident power and reflected power from the surfaces of TCCRs as a function of angle (θ_c)

One of the likely scenarios for the practicable implementation of the mechanism could be in recharging the batteries of mobile robots in indoor environment like factory, where BS is installed with ceiling of the factory and optically unicasts or broadcasts as well as recharges the batteries from time to time on the fly without having to interrupt the on-going operation. The recharging is performed by using variable IR laser, two passive devices, CCRs and TCCRs mounted on every main sensor node. The power absorbed by TCCR is used for recharging thin-film battery. This additional and most important benefit of passive optical wireless communication becomes main motivation of this work. This is an initial proposal towards the development of this efficient communication and recharging mechanism. The details of this communication model is still need to be explored like maximum possible degree of freedom of CCRs and TCCRs, and their possibility of supporting the required of network. Hopefully, a sustained effort would develop a strong theoretical base and transform it into a practical workable network, which make backbone sensor nodes more reliable. One of the possible future directions of research is in exploring the possibilities of recharging the mobile wireless sensor network.

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