

Optical Wireless Sensor Network System Using Corner Cube Retroreflectors

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We analyze an optical wireless sensor network system that uses corner cube retroreflectors (CCRs). A CCR consists of three flat mirrors in a concave configuration. When a light beam enters the CCR, it bounces off each of the three mirrors, and is reflected back parallel to the direction it entered. A CCR can send information to the base station by modulating the reflected beam by vibrating the CCR or interrupting the light path; the most suitable transmission format is on-off keying (OOK). The CCR is attractive in many optical communication applications because it is small, easy to operate, and has low power consumption. This paper examines two signal decision schemes for use at the base station: collective decision and majority decision. In collective decision, all optical signals detected by the sensors are received by one photodetector (PD), and its output is subjected to hard decision. In majority decision, the outputs of the PDs associated with the sensors are subjected to hard detection, and the final data is decided by majority decision. We show that increasing the number of sensors improves the bit error rate (BER). We also show that when the transmitted optical power is sufficiently large, BER depends on sensor accuracy. We confirm that collective decision yields lower BERs than majority decision.

Keywords and phrases: corner cube retroreflector, optical wireless sensor network, collective decision, majority decision.

1. INTRODUCTION

Recently, sensor networks consisting of small sensors that have the abilities of detection, data processing, and communication have attracted much attention owing to the development of wireless communications and electric devices [1, 2]. Since wireless sensor networks have several advantages, such as autonomous distributed control, network extensibility, and simple setup, their use to realize surveillance and security in various places, such as hospitals, dangerous areas, and polluted areas, is expected. However, since the electric power, memory, and throughput of the sensor itself are restricted, we need to improve its power efficiency. Therefore, the use of passive transmitters such as the corner cube retroreflector (CCR), which do not have a light source in the sensor itself, is attractive for improving the power efficiency of the sensor. An ideal CCR consists of three mutually orthogonal mirrors that form a concave corner. A CCR, as a

micro machine, has attracted much attention because of the following advantages: small size, ease of operation, and low power consumption (lower than 1 nJ/bit). It is most often used in distance measurement systems. When a light beam enters the CCR, it bounces off each of the three mirrors, and is reflected back parallel to the direction it entered [3]. A CCR can send an optical signal to the base station by modulating the reflected beam through techniques such as vibrating the CCR or interrupting the light path to create on-off-keying (OOK) modulated optical signals. Pister analyzed the signal-to-noise-ratio (SNR) of the optical wireless sensor network system, where the transceiver and CCR have a one-to-one correspondence, however, the accuracy of the observation at the sensor was not considered [4]. Karakehayov proposed an optical wireless sensor network system where the transceiver and CCR have a one-to-one correspondence. Unfortunately, the paper did not address the performance [5].

The problem of distributed detection in wireless sensor networks has been the subject of several recent studies [6, 7]. It is well known that the deployment of multiple sensors for signal detection in a surveillance application may substantially enhance system survivability, improve detection

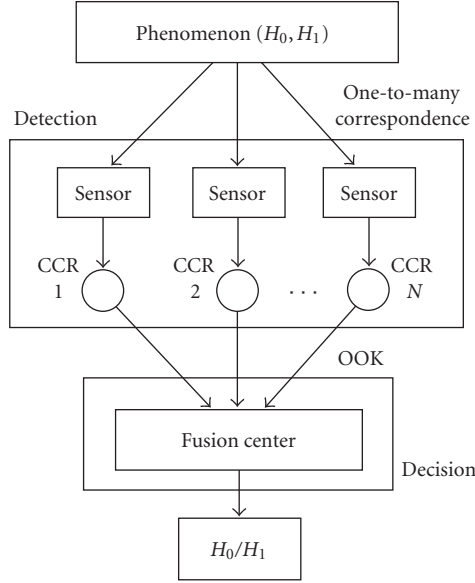


FIGURE 1: Optical wireless sensor network model with CCRs.

performance, shorten decision time, and provide other benefits [6]. Figure 1 shows the optical wireless sensor network model that pairs one decision center (transceiver) with many CCRs. We note that this one-to-many correspondence between the transceiver and CCR has been neither proposed nor evaluated in any other paper. In this figure, the local decision made on each CCR stream is communicated to the decision system. Upon receiving this binary information, the decision system combines the local decisions and arrives at the final decision according to a rule. The performance of the distributed detection scheme is usually measured by a function involving the probability of making an incorrect decision.

In this paper, we analyze the bit error rate (BER) of an optical wireless sensor network system that uses the one-to-many transceiver-CCR configuration as shown in Figure 1. We evaluate two approaches to implementing the decision system: collective decision and majority decision. In collective decision, all optical signals are received by one photodetector (PD), and a hard decision is made on the PD output. In majority decision, the output of each PD associated with a sensor is subjected to hard decision and the final data yielded by taking a majority decision on the hard decision outputs. We show that BER is improved by increasing the number of sensors. We also show that when the transmitted optical power is sufficient, BER depends on sensor accuracy. We confirm that BER is improved by using collective decision rather than majority decision.

2. SENSOR ACCURACY

We consider a distributed detection system with N sensors, N CCRs, and one fusion center arranged in a parallel structure (see Figure 1). Each detector employs a predetermined local decision rule, and we assume that, conditioned on each

hypothesis, the local binary decisions are statistically independent. First, we analyze the accuracy of the sensors. We consider two hypotheses H_0 and H_1 . The i th CCR transmits bit 0 or 1, which is detected by the i th sensor, if it favors hypotheses H_0 or H_1 , respectively. The a priori probabilities of the two hypotheses, H_0 and H_1 , are denoted by $P(H_0)$ and $P(H_1)$, respectively, where $P(H_0) + P(H_1) = 1$. At each CCR unit, sensor output is analog-to-digital (A/D) converted and OOK modulated. The modulated optical signals are sent to the fusion center.

$p(x|H_i)$ denotes the conditional probability density function (pdf) of the observation of each sensor, H_i . We assume the observation to be Gaussian distributed (Gaussian observation). We also assume that the means of the observation of H_0 and H_1 are 0 and 1, respectively, and that the variance of the observation for either event is σ_s^2 . The conditional pdfs are expressed as [8]

$$p_0(x) = p(x|H_0) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left(-\frac{x^2}{2\sigma_s^2}\right),$$

$$p_1(x) = p(x|H_1) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left(-\frac{(x-1)^2}{2\sigma_s^2}\right). \quad (1)$$

3. LINK ANALYSIS

We analyze the SNR of the above optical wireless sensor network [4]. The single laser at the transceiver emits a beam of power P_t with semiangle of illuminated field θ_f . We denote the horizontal distance between the laser and the n th CCR by r , the angle between the laser and the axis of the link by $\theta_{s,n}$, the link distance between the laser and n th CCR by $r/\cos\theta_{s,n}$ and the effective diameter of CCR by d_c . Note that the system uses a single source. We assume the light path to be line of sight and that all light paths arrive at PD at the same time. The optical power captured by the n th CCR is expressed as

$$P_{cc,n} = \frac{P_t d_c^2 \cos^2 \theta_{s,n} \cos \theta_{c,n}}{4r^2 \tan^2 \theta_f}, \quad (2)$$

where $\theta_{c,n}$ represents the angle between the center of the beam and the axis of the link and d_c represents the effective diameter of CCR (not tilted). Considering multiple reflection, we assume that the CCR has effective reflectivity R_c . The CCR modulates the cw downstream signal into an OOK signal with non-return-to-zero (NRZ) pulses. Assuming that 0 and 1 are equiprobable, the average power reflected by the n th CCR is given by $P_{c,n} = R_c P_{cc,n}/2$. Using the Fraunhofer diffraction theory [9], the diffracted irradiance at the lens as reflected by the n th CCR is expressed as

$$I_{l,n} = \frac{P_{c,n} \pi d_c^2 \cos^2 \theta_{s,n} \cos \theta_{l,n}}{4\lambda^2 r^2}, \quad (3)$$

where $\theta_{l,n}$ represents the angle between the axis of the link and the direction to the camera lens, and λ represents the interrogation wavelength. In this paper, we neglect imperfection in the CCR and any atmospheric attenuation. We assume that the camera employs an optical bandpass filter with

bandwidth $\Delta\lambda$ to reject ambient light. The average received photocurrent reflected by the n th CCR is given by [4]

$$i_{\text{sig},n} = \frac{I_{l,n}\pi d_l^2 T_l T_f f_{\text{act}} R}{4}, \quad (4)$$

where T_l represents the effective transmission of the camera lens, T_f represents the optical filter transmission, f_{act} represents the fraction of the camera pixel area that is active, R represents the pixel responsivity, and d_l represents the effective diameter of lens (not tilted).

We assume that the region around the CCR is illuminated by the ambient light with power spectral density (PSD) p_{bg} , and that this region reflects the ambient light with reflectivity R_{bg} . Within the bandwidth of the optical bandpass filter, the photocurrent per pixel due to ambient light is given by [4]

$$i_{\text{bg},n} = \frac{\pi p_{\text{bg}} R_{\text{bg}} \Delta\lambda \tan^2 \theta_f d_l^2 T_f T_l f_{\text{act}} R}{4N}, \quad (5)$$

where N is the number of CCRs and Δ is the optical bandpass filter's bandwidth. The ambient light induces the white shot noise having a one-sided PSD $S_{\text{bg}} = 2qi_{\text{bg}}$. The load resistance R_F depends on the white noise having PSD given by [10]

$$S_R = \frac{4k_B T}{R_F}, \quad (6)$$

where k_B is Boltzmann's constant and T is the absolute temperature. The preamplifier contributes to the white noise with PSD S_{amp} . Thus, the total variance is given by [10]

$$\sigma_{\text{tot}}^2 = (S_{\text{bg}} + S_R + S_{\text{amp}}) R_b, \quad (7)$$

where R_b is the bit rate. The noise is dominated by approximately equal contributions from ambient light shot noise and thermal noise from the feedback resistor; the amplifier noise is negligible.

The peak electrical SNR is given by [3]

$$\text{SNR} = \frac{i_{\text{sig}}^2}{\sigma_{\text{tot}}^2}. \quad (8)$$

The BER of link P_{link} is given by [4]

$$P_{\text{link}} = Q(\sqrt{\text{SNR}}), \quad (9)$$

where $Q(x) = \text{erfc}(x/\sqrt{2})/2$.

4. DECISION METHODS ANALYSIS

4.1. Collective decision

Figure 2 shows the fusion center model with collective decision. In collective decision, all optical signals are received by one PD, and then a hard decision is made on the PD's output. If the total received signal has optical intensity larger than the hard decision threshold for the system using collective decision θ_{col} , it is judged as 1. The BER of the system

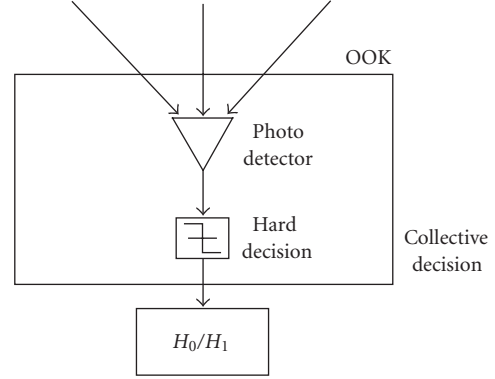


FIGURE 2: Model of the decision system using collective decision.

using collective decision P_{col} is given by

$$P_{\text{col}} = P(H_0) \sum_{i=0}^N [P(i|H_0) \cdot P(s_{\text{all}} \geq \theta_{\text{col}} | H_0, i)] \\ + P(H_1) \sum_{i=0}^N [P(i|H_1) \cdot P(s_{\text{all}} \leq \theta_{\text{col}} | H_1, i)],$$

$$P(s_{\text{all}} \geq \theta_{\text{col}} | H_0, i) = \int_{\theta_{\text{col}}}^{\infty} \left[\frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-i)^2}{2\sigma^2}\right) \right],$$

$$P(s_{\text{all}} \leq \theta_{\text{col}} | H_1, i) = \int_{-\infty}^{\theta_{\text{col}}} \left[\frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-N+i)^2}{2\sigma^2}\right) \right], \quad (10)$$

where $P(H_0)$ and $P(H_1)$ represent the a priori probabilities of the two hypotheses, N represents the number of CCRs, i represents the number of CCRs deciding 1, and s_{all} represents the total received power at the PD.

4.2. Majority decision

Figure 3 shows the fusion center model with majority decision. In majority decision, the output of each PD is subjected to hard detection and the resulting data is processed by majority decision. The BER of the system using majority decision, P_{maj} , is given by

$$P_{\text{maj}} = P(H_0) \sum_{i=0}^N \sum_{j=\lfloor N/2+1 \rfloor}^N [P(i|H_0) \cdot P(j|H_0, i)] \\ + P(H_1) \sum_{i=0}^N \sum_{j=\lfloor N/2+1 \rfloor}^N [P(i|H_1) \cdot P(j|H_1, i)], \quad (11)$$

where i represents the number of CCRs deciding 1 and j represents the number of CCRs decided by the receiver as having sent 1. Note that when the threshold of each sensor is set appropriately and each sensor has the same conditional observation pdf, assumed to have Gaussian distribution, the optimal threshold is uniquely decided. Thus, adaptive thresholding does not improve the performance of majority voting under the assumptions used in this paper.

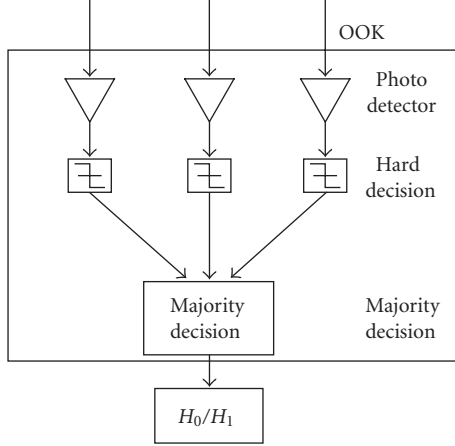


FIGURE 3: Model of the decision system using majority decision.

4.3. Floor probability

We consider the floor probability of the sensor network system where we define the floor probability as the BER at which there is no channel error. Regardless of the decisions, the floor probability of the system depends on sensor accuracy. The floor probability P_{floor} is derived as

$$P_{\text{floor}} = P(H_0)P(i > t_f | H_0) + P(H_1)P(i \leq t_f | H_1), \quad (12)$$

$$P(i > t_f | H_0) = \sum_{i=t_f+1}^N \binom{N}{i} \left(\int_{t_s}^{\infty} p_0(x) dx \right)^i \left(\int_{-\infty}^{t_s} p_0(x) dx \right)^{N-i}, \quad (13)$$

$$P(i \leq t_f | H_1) = \sum_{i=0}^{t_f} \binom{N}{i} \left(\int_{t_s}^{\infty} p_1(x) dx \right)^i \left(\int_{-\infty}^{t_s} p_1(x) dx \right)^{N-i}, \quad (14)$$

where i represents the number of CCRs deciding 1, t_s represents the local threshold of the sensor, t_f represents the threshold at the fusion center. Note that $t_f = \lfloor N/2 \rfloor$ for deriving the floor probability irrespective of the decisions.

5. NUMERICAL RESULTS

In this section, we evaluate the BER of the above optical wireless sensor network system. We evaluate two decision techniques: collective decision and majority decision. We assume that all sensors observe the same environment (received optical power, incident angle, reflected angle, and so on). Table 1 shows the parameters of the optical wireless sensor network systems. Figure 4 shows the optical wireless sensor network system using CCRs.

5.1. BER versus transmitted optical power

Figure 5 shows the BERs versus the transmitted optical power with collective decision, where $\sigma_s^2 = 1$. The solid lines plot BERs and the dashed lines plot the floor probabilities of the

TABLE 1: The parameters of optical wireless sensor network system.

Description	Typical value
Effective diameter of CCR (not tilted)	$d_c = 5 \times 10^{-4}$ m
Effective diameter of lens (not tilted)	$d_l = 0.1$ m
Effective reflectivity of CCR	$R_c = 0.85$
Effective transmission of camera lens	$T_l = 0.8$
Optical filter transmission	$T_f = 0.8$
Fraction of camera pixel area that is active	$f_{\text{act}} = 0.75$
Pixel responsivity	$R = 0.5$ A/W
Angle between laser and axis of link	$\theta_c = 60$ degree
Angle between center of beam and direction to CCR	$\theta_c = 60$ degree
Angle between axis of link and direction to camera lens	$\theta_l = 60$ degree
Interrogation wavelength	$\lambda = 830$ nm
Link range	$r = 500$ m
Semiangle of illuminated field	$t_f = 1$ degree
Ambient light spectral irradiance	$p_{\text{bg}} = 0.8$ W/(m ² ·nm)
Reflectivity of background behind CCR	$R_{\text{bg}} = 0.3$
Optical bandpass filter bandwidth	$\Delta = 5$ nm
Number of pixels in image sensor	$N = 10^5$
Boltzmann's constant	$k_B = 1.38 \times 10^{-23}$ J/K
Absolute temperature	$T = 300$ K
Feedback resistance	$R_F = 20$ M Ω
Bit rate	$R_b = 1$ kbps

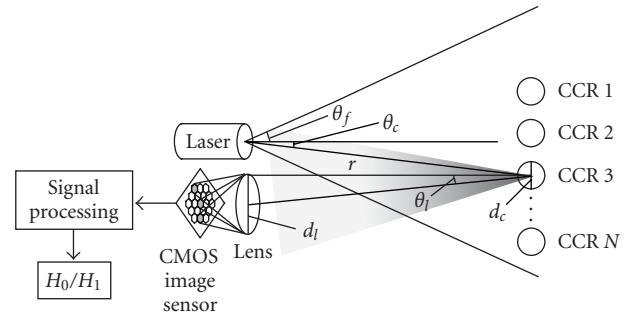


FIGURE 4: Optical wireless sensor network system model with CCR.

system. In Figure 5 we can see that the BERs of the system are improved as the number of CCRs increases. We can also see that when the transmitted optical power is sufficiently large, BER depends on sensor accuracy and equals the floor probabilities of the system as derived by (12).

Figure 6 shows the BERs versus the transmitted optical power with majority decision, where $\sigma_s^2 = 1$. The trends seen match those in Figure 5; BER improves with the number of CCRs. When the transmitted optical power is sufficiently large, BER depends on sensor accuracy. For instance, at the transmitted optical power of 5 W and with 100 CCRs, the BERs are 5×10^{-5} and 3×10^{-3} with collective decision and majority decision, respectively. Comparing Figures 5 and 6, we can confirm that collective decision yields better BER than majority decision.

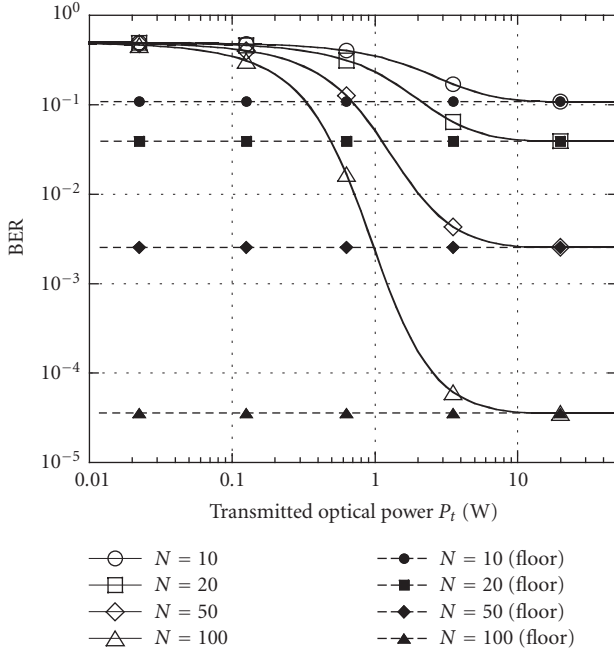


FIGURE 5: BER versus transmitted optical power with collective decision.

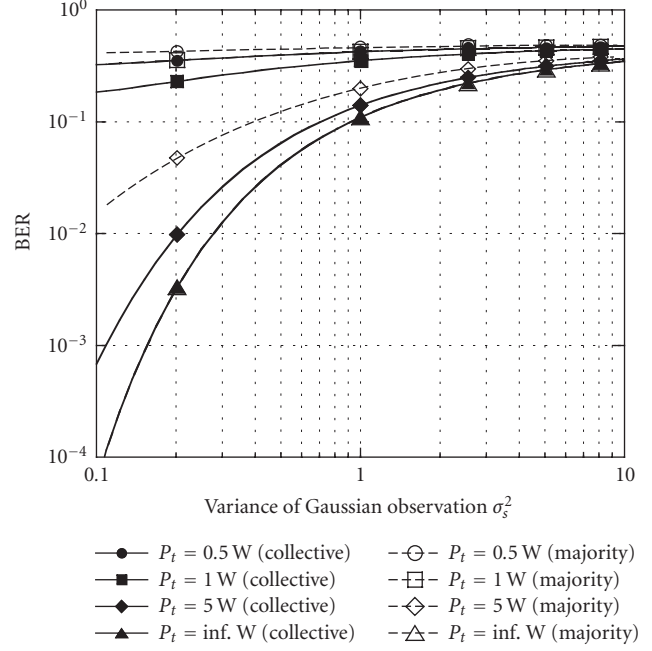


FIGURE 7: BER versus the variance of Gaussian observation ($N = 10$).

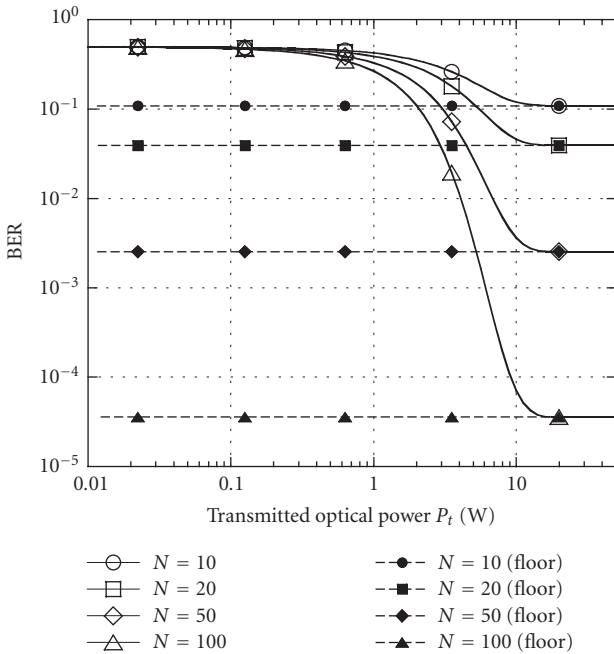


FIGURE 6: BER versus transmitted optical power with majority decision.

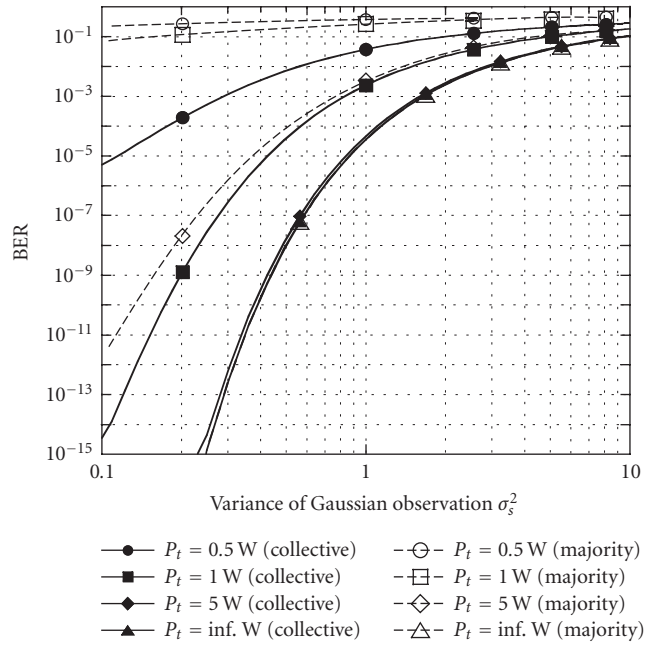


FIGURE 8: BER versus the variance of Gaussian observation ($N = 100$).

The limitations placed on BER are as follows. As we noted previously, we have neglected imperfection in the CCR and any atmospheric attenuation. As the number of sensors goes to infinity, the floor probability becomes zero under the assumption, which is derived by the central limit theorem [11]. When the transmitted optical power is adequately large, the

BERs depend on the accuracy of the sensors and converge to the floor probabilities, as shown in Figures 5 and 6.

5.2. BER versus variance of Gaussian observation

Figures 7 and 8 show the BERs of the systems versus the variance of Gaussian observation for systems using collective

decision and majority decision with 10 and 100 sensors. The solid (dashed) lines plot the BER with collective (majority) decision. Note that at the transmitted power of 1 W, BER equals the floor probabilities of the systems as derived by (12). Sensor accuracy depends on the variance of the Gaussian observation. We can see that BER improves with the number of sensors. For instance, at the variance of Gaussian observation of 0.5, transmitted optical power of 5 W, and collective decision, the BERs are 6×10^{-2} and 2×10^{-8} for 10 and 100 sensors, respectively. We can also see that BER improves as the variance of the Gaussian observation decreases. Note that collective decision yields better BER than majority decision.

6. CONCLUSIONS

We analyzed an optical wireless sensor network system based on corner cube retroreflectors (CCRs). A CCR can send information to the base station by modulating the reflected beam via vibration of the CCR or interruption of the light path, and one can transmit an on-off-keying (OOK) modulated optical signal. Our analysis evaluated two decision techniques: collective decision and majority decision. We showed that for both techniques, BER improves with the number of sensors. We also showed that when the transmitted optical power is sufficiently large, bit error rate (BER) depends on the accuracy of the sensors. We confirmed that collective decision yields better BER than majority decision.

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