A Link Quality Inference Model for IEEE 802.15.4 Low-Rate WPANs

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***Abstract*—Accurate estimation of PHY conditions would allow for better cross-layer resource management and provisioning. Unfortunately, Commercial-of-the-Shelf (COTS) typically provide very limited information. We utilize measurement studies to decipher LQI readings available in Zigbee radios with CC2420 chipset. Then, we verify the relationship between LQI readings and CORR derived from our analytical model. Second, an analytical model is developed to predict SER for packet transmission under different channel models with the instantaneous LQI readings. We believe this model will lead to more informed resource management decisions in Zigbee radio networks. Both simulations and measurement studies support the proposed model.**

I. Introduction

One major challenge that wireless network designers and operators are facing is the real-time estimation of PHY and MAC characteristics. Commercial-of-the-Shelf (COTS) devices typically only provide limited information regarding the current condition of wireless channels. The lack of detailed PHY knowledge for better cross-layer resource management and provisioning leads to misinformed decisions. For instance, most wireless interfaces cannot distinguish received signal strength from interference in a single $RSSI$ snumber[1]. Based on the assumption that $RSSI$ reflects received signal strength and there is a correlation between received signal strength with signal-to-noise ratio (SNR), many studies suggest to use $RSSI$ information for rate adaptation or selection of good routes for packet forwarding [1]-[3].

To find out the relationship of $RSSI$ to the receive signal strength and interference level, we have conducted measurements using TmoteSky sensors with CC2420 Zigbee radio interfaces [4] and USRP2 [5] boards programmed with GNU Radio software. In the measurements, one fixed node acts as a transmitter and second node operates as a receiver. In addition to the fixed transmitted signal, controllable Gaussian noise from USRP2 is also injected to the receiver via coaxial cable. The generated noise level in USRP2 is varied. At each noise level, a thousand packets of length 40 bytes are transmitted and two types of $RSSI$ readings are recorded, **signal** $RSSI$ and **noise floor**[2]. The first one corresponds to the received signal strength reported by the Zigbee radio during packet transmissions while the second one reports the power of ambient noise recorded between packets. CH26

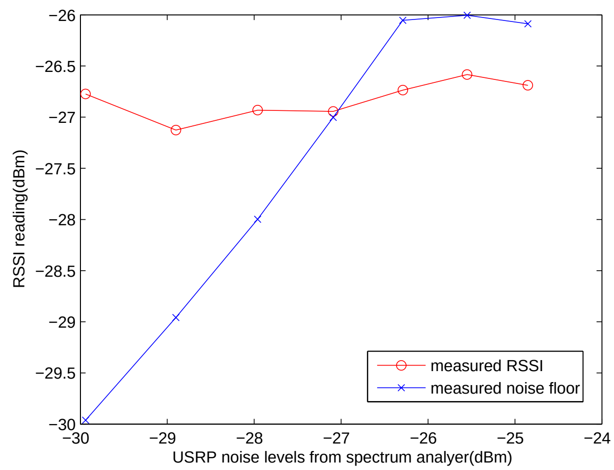

Fig. 1. Zigbee signal $RSSI$ and noise floor readings

is used in the experiments to avoid unintended interference from the campus WiFi network. Packet errors are detected using the cyclic redundancy check (CRC). Symbol error rate (SER) is determined by comparing the known bit pattern in the transmitted packets with the received packets. Agilent spectrum analyzer N9020A is also used in the measurements for cross validation.

Figure 1 shows the signal $RSSI$ and noise floor with respect to the controllable noise levels of USRP2 in Channel 26 (2.479GHz - 2.481GHz). From the figures, a few observations can be made. Firstly, the measured noise floor is not linear with the actual noise floor due to quantization errors and some other unknown factors. Secondly, as the noise floor grows, $RSSI$ readings increase. This is consistent with the observations made by other researchers [7]-[9]. Thirdly, in contrast to the conventional wisdom that $RSSI$ readings are the sum of the actual received signal strength and the noise floor, Figure 1 shows that in some cases, the noise floor in fact exceeds $RSSI$ readings. Therefore, the difference between $RSSI$ and noise floor readings does not constitute a reliable measure to predict the signal to noise ratio.

To address the deficiency of $RSSI$ in predicating link quality, authors in [10]-[12] suggest the use of link quality indication (LQI), which is an output required by the IEEE 802.15.4 protocol to indicate the quality of a received packet.

[1]Roughly speaking, separation of the two requires subtraction of useful signal from the total received signal strength after decoding.

[2]In this paper, we do not distinguish noise from interference.

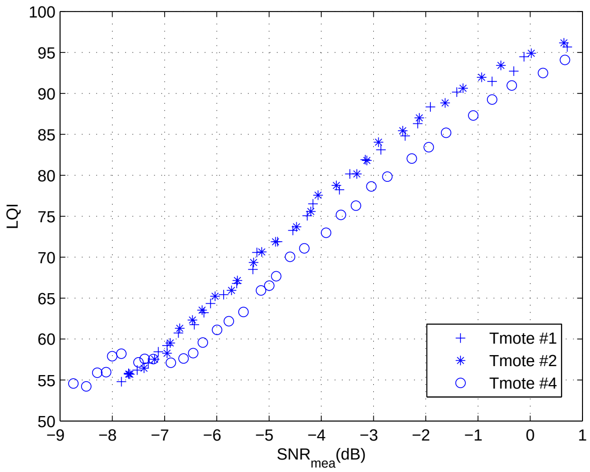

Fig. 2. IEEE 802.15.4 $RSSI$ measurements in cabled environment on channel 26

In the CC2420 datasheet [4], a correlation value ($CORR$) is supplied by the chip that "*provides an average correlation value for each incoming packet, based on the 8 first symbols following the start of frame delimiter*". Furthermore, "*software must convert the correlation value to the range 0–255 by computing $LQI = (CORR - a) * b$, where a and b are found empirically based on PER measurements as a function of correlation value(presumedly by each manufacturer separately)*". However, the fundamental question remains, *how to use LQI to predict link quality? On the practical side, how to determine a and b?*

The contribution of this paper is two-fold. First, we reverse engineer the LQI measurements in 802.15.4 Zigbee radios and determine how LQI is actually derived. We establish the relationship between the LQI readings reported by CC2420 and $CORR$ derived from our analytical model through measurement studies. Second, we develop an analytical model that relates LQI values with SER/PER for packet transmission under different channel models, namely, AWGN, Rician and Rayleigh. This model allows us to predict real channel quality based on instantaneous measurements of LQI currently available from Zigbee chips.

The rest of the paper is organized as follows. In Section II, we unravel the relationship between LQI and SNR. In Section III, an analytical model for SER and PER is developed to predict link quality using LQI and validated via the simulations. Experimental studies are provided in Section IV followed by conclusion in Section V.

II. LQI UNRAVELED

In this section, we try to answer the questions through measurement studies, i) what is LQI exactly? and ii) how is LQI derived from the received data?

A. Measurement study

We conducted further cabled experiments using TmoteSky nodes, USRP2 supported by GNU Radio, Agilent spectrum analyzer N9020A and other basic circuit components. Again, the noise is injected by a signal generator implemented in USRP2. In addition to controlling the noise floor, we further control the received signal strength using commercial microwave-rated attenuators. In all experiments, the SNR is determined from the signal strength and noise floor measured directly from a spectrum analyzer across a 2MHz bandwidth.

Figure 2 shows the relationship between the measured LQI and measured SNR for three TmoteSky Zigbee nodes. The curves of all three nodes are approximately linear and are close to one another.The small gap between the curves of Tmote #4 and the others is likely due to manufacturing artifacts. Thus, we can model LQI measurement(dBm) and SNR (dB) as:

$$LQI = p1 \times SNR + p2, \qquad (1)$$

where p=[p1 p2] are the factors obtained using linear regression. From the experiments, we have p1 = 5.3145, p2 = 97.0477.

From the measurement results, we conclude that the LQI readings in Zigbee chipsets reflect the instantaneous SNR values at the receiver. This is seemingly inconsistent with the specification, which states that the LQI is calculated from the CORR values from the first 8 symbols. Next, we provide an analytical study to support our claim that these two are in fact in line with one another.

B. Analytical model

Preliminaries of 802.15.4: The IEEE 802.15.4 is a standard for low-rate wireless personal area networks (LR-WPANs). Its PHY operates in the ISM bands, and uses 16-ary *quasi-orthogonal* modulation. A 32-chip *direct sequence spread spectrum* (DSSS) code is used to spread the signal and achieve both processing coding and processing gain. Bits come from the physical protocol data unit (PPDU), which handles the physical framing, at a data rate of 250 kbit/s. The bits get converted to data symbols of 4 bit, and each symbol is spread according a given spreading sequence. Before transmitting, the stream of chips (at rate 2 Mchip/s) are modulated on the carrier using *offset quadrature phase shift keying* (OQPSK) with *half-sine pulse shaping*. A non-coherent receiver is typically used to demodulate the OQPSK signal, which is then passed into a clock recovery block and output symbols for slicing. After chip to symbol despreading, the MAC Protocol Data Unit (MPDU) is recovered.

In this paper, we are interested in the baseband process of decoding symbols after the demodulator and model the modulator/demodulator as part of the channel.

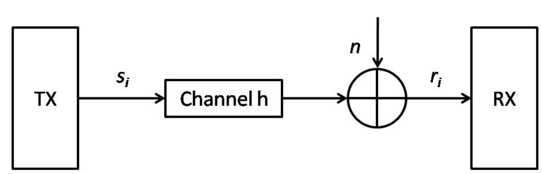

Fig. 3. Basic communication model

The received signal at RX is described as:

$$\vec{r_i} = h\vec{s_i} + \vec{n} \quad (2)$$

where h is channel response, $\vec{n}$ is additive Gaussian white noise vector, $n_k \sim \mathcal{N}(0, \sigma_n^2), k = 1, 2, ..., N$. Note that $\vec{s_i}$, $\vec{n}$ and $\vec{r_i}$ are $N \times 1$ vectors, respectively. N is the number of chips, i.e., $N = 32$.

Thus, the received signal power and noise power per symbol can be computed as:

$$P_s = \langle h\vec{s_i}, h\vec{s_i} \rangle = C_{ii}h^2, \quad P_n = N * 2\sigma_n^2 = 64\sigma_n^2 \quad (3)$$

The received SNR is calculated as:

$$\rho = \frac{P_s}{P_n} = \frac{C_{ii}h^2}{64\sigma_n^2} = \frac{h^2}{2\sigma_n^2} \quad (4)$$

Derivation of Chip Correlation: Based on the CC2420 datasheet [4], we define the chip correlation as follows,

$$CORR = \frac{1}{8}\sum_i \max_j \langle \vec{r_i}, \vec{s_j} \rangle \quad (5)$$

In other words, $CORR$ is the inner product between the received signal with the symbol (possibly erroneous) that has the maximum correlation, and then averaged over first 8 symbols following the start of frame delimiter (SFD) [4].

If we define

$$\begin{aligned} \upsilon_{ij} &= \langle \vec{r_i}, \vec{s_j} \rangle = hC_{ij} + n^T s_j \\ Z_i &= \max_j \upsilon_{ij} \end{aligned} \quad (6)$$

Then υ_{ij} is a Gaussian random variable with mean and variance:

$$\begin{aligned} E(\upsilon_{ij}) &= E(hC_{ij} + n^T s_j) = hC_{ij} \\ Var(\upsilon_{ij}) &= Var(hC_{ij} + n^T s_j) = \sigma_n^2 C_{jj} \end{aligned} \quad (7)$$

For fixed i, $\vec{\upsilon_i} = [\upsilon_{i1}, \upsilon_{i2}, ..., \upsilon_{iN}]$ is a multi-dimensional Gaussian random vector, with joint probability density function (PDF) as:

$$f_{\vec{\upsilon}_i}(\upsilon_{i1}, \upsilon_{i2}, ..., \upsilon_{iN}) = \frac{1}{(2\pi)^{N/2}\det(\Sigma)^{1/2}} e^{-\frac{1}{2}(\vec{\upsilon}_i - \vec{\mu})^\intercal \Sigma^{-1}(\vec{\upsilon}_i - \vec{\mu})} \quad (8)$$

The covariance matrix Σ has non-zero off-diagonal elements. More specifically, $\Sigma_{kk} = Var(\upsilon_k) = \sigma_n^2 C_{kk}$, and $\Sigma_{kl} = \sigma_n^2 C_{kl}$.

Determination of the distribution of $Z_i = \max_j(\upsilon_{ij})$ is non-trivial since Z_i may not be the symbol sent. However, in a relatively good channel environment, we assume the perfect decoding, in which Z_i always returns the max correlation of the symbol actually sent. Therefore, the mean and variance of $CORR$ can be presented as:

$$\begin{aligned} \mu_{CORR} &\approx \frac{1}{8}\sum_i E\left[\langle hs_i + n, s_i \rangle\right] = hC_{ii} \\ \sigma_{CORR}^2 &\approx \frac{1}{8} Var\left[\langle hs_i + n, s_i \rangle\right] = \frac{1}{8}C_{ii}\sigma_n^2 = 4\sigma_n^2 \end{aligned} \quad (9)$$

Combining with (4), we can obtain the approximated SNR in terms of μ_{CORR} and σ_{CORR}, as follows:

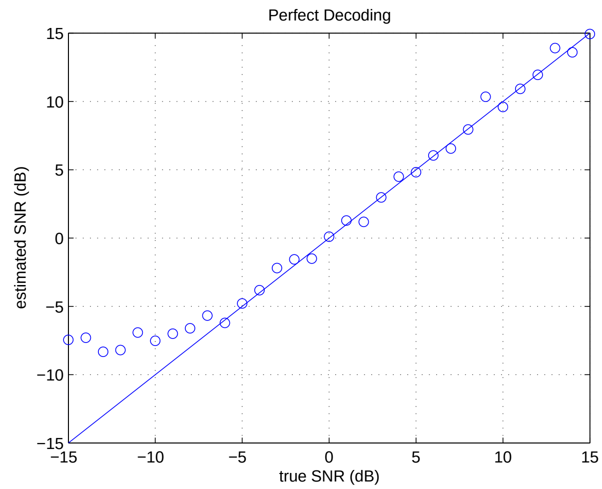

Fig. 4. The estimated $SNRs$ from CORR

$$SNR_{est} = \frac{2\mu_{CORR}^2}{C_{ii}^2 \sigma_{CORR}^2} \quad (10)$$

Simulation validation: Simulations are setup based on the IEEE 802.15.4 standard [6], with focus on the encoding and decoding procedure. The fading channel is assumed to be flat and the noise floor is approximately -111dBm[3]. We vary the channel gain h or transmitted signal power to represent different locations. For each location, 1000 packets are sent from TX to RX independently, each has 40 symbols. Symbol-by-symbol decoding is conducted by finding the one with the maximum correlation with the received symbol.

Figure 4 shows the estimated SNR from (10) and the true SNR averaged over 100 packets. As shown in the figure, the perfect decoding obtains good accuracy in approximating SNR when SNR is larger than -5dB. The difference between the estimated and true SNR becomes larger in the low SNR regime. This is mainly because that the perfect decoding assumption no longer holds.

To this end, we have established an approximation for the relationship between SNR_{est} and μ_{CORR} as well as σ_{CORR} for the IEEE 802.15.4 Zigbee radio. From (10), we see that SNR is linear with respect to the ratio of the square of the mean and variance of the $CORR$. Recall that the measurement study shows that SNR is roughly linear to LQI. This implies that LQI can be determined by the mean and variance of $CORR$ values for $SNR > -5dB$.

III. Prediction of Link Quality using LQI

Now we are in the position to determine link quality from LQI. The SER measure typically defines for link quality. We can also compute BER and PER based on SER.

At the receiver, a symbol error occurs when the symbol decoded is not the same as the transmitted one. Thus, let $\langle x, y \rangle$

[3]For Zigbee system in 2.4GHz with 2MHz bandwidth, $NF(dBm) = -174 + 10log_{10}(BW)$ is used for a lower bound on the noise floor level.

be the inner product of vector x and y, SER can be derived as,

$$P_{e|(i,j)} = Prob\{\langle \vec{r_i}, \vec{s_i} \rangle < \langle \vec{r_i}, \vec{s_j} \rangle \mid TX sent\, i, RX decide\, j\} \quad (11)$$

where r_i is the received signal when i symbol is sent, s_i and s_j are binary chip sequences for the ith and jth symbol ($i \neq j$), respectively. Applying (2), we have

$$\begin{aligned} P_{e|(i,j)} &= Prob\{\langle h\vec{s_i} + \vec{n}, \vec{s_i} \rangle < \langle h\vec{s_i} + \vec{n}, \vec{s_j} \rangle \mid (i,j)\} \\ &= Prob\{hC_{ii} + \langle \vec{n}, \vec{s_i} \rangle < hC_{ij} + \langle \vec{n}, \vec{s_j} \rangle \mid (i,j)\} \\ &= Prob\{(\vec{s_j} - \vec{s_i})^T \vec{n} > h(C_{ii} - C_{ij}) \mid (i,j)\}, \end{aligned} \quad (12)$$

where $C_{ij} \triangleq \langle \vec{s_i}, \vec{s_j} \rangle$.

Since $\vec{n}$ is a vector of independent Gaussian random variables, $n_x = (\vec{s_j} - \vec{s_i})^T \vec{n}$ is also Gaussian distributed with expectation and variance as:

$$\begin{aligned} E(n_x) &= E[(\vec{s_j} - \vec{s_i})^T \vec{n}] = 0 \\ Var(n_x) &= E(n_x^2) - E(n_x)^2 = E[(\vec{s_j} - \vec{s_i})^T \vec{n}\vec{n}^T (\vec{s_j} - \vec{s_i})] \\ &= \sigma_n^2 E[\vec{s_j}^T \vec{s_j} - \vec{s_j}^T \vec{s_i} - \vec{s_i}^T \vec{s_j} + \vec{s_i}^T \vec{s_i}] \\ &= 2\sigma_n^2 (C_{ii} - C_{ij}) \end{aligned} \quad (13)$$

Clearly, $C_{ii} > C_{ij}$. Given a specific i and j, the SER can be further written as the tail probability:

$$P_{e|(i,j)} = Q\left[\sqrt{\frac{h^2(C_{ii} - C_{ij})}{2\sigma_n^2}}\right] \quad (14)$$

Assuming that the symbol error is dominated by the nearest neighbors (In Zigbee system, i.e., the neighbors with cross-correlation equal to ± 8 in the correlation matrix (Table I)), we can approximate for each transmitted symbol i the conditional error probability is,

$$\begin{aligned} P_{e|i} = \sum_j P_{e|(i,j)} P(j) &\approx 128 * \frac{1}{16} * Q\left(\sqrt{\frac{h^2(C_{ii} - C_{ij})}{2\sigma_n^2}}\right) \\ &= 8Q\left(\sqrt{\frac{3C_{ii}h^2}{8\sigma_n^2}}\right) \end{aligned} \quad (15)$$

Therefore, under the assumption that all symbols are transmitted with equal probability, the SER is given by,

$$P_{SER} = \sum_i P_{e|i} P(i) = 8Q\left(\sqrt{\frac{3C_{ii}h^2}{8\sigma_n^2}}\right), \quad (16)$$

where $C_{ii} = 32, \forall i$ is the autocorrelation of the ith symbol.

After applying (4), we can rewrite (16) as:

$$P_{SER} = 8Q\left(\sqrt{24\rho}\right). \quad (17)$$

Note that, (17) is the general formula of the symbol error rate in the IEEE 802.15.4, where h depends on different channel models, e.g., for $AWGN$ channel, h=1.

The Rayleigh fading channel with no line-of-sight (LOS) can be modeled as a complex Gaussian random variable $h \sim \mathcal{CN}(0, \sigma^2)$ [14], where the pdf of amplitude is given by:

$$f(r) = \frac{r}{\sigma^2} exp\left(\frac{-r^2}{2\sigma^2}\right), r \geq 0 \quad (18)$$

and the square of the amplitude is exponentially distributed [14]. Thus, for standard Rayleigh fading where $\sigma = 1$, the corresponding SER can be computed as:

$$P_{SER} = E_{\|h\|}\left[8Q(\sqrt{24\rho})\right] = 4\left(1 - \frac{1}{\sqrt{\sigma_n^2/6 + 1}}\right) \quad (19)$$

Similarly, for Rician channel, the SER can be expressed as [15]:

$$\begin{aligned} P_{SER} = \frac{1}{M} \sum_{i=2}^{M} (-1)^i \binom{M}{i} \frac{(1+K)/\rho}{(1+K)/\rho + 1 - 1/i} \\ \cdot exp\left(-\frac{K(1-1/i)}{(1+K)/\rho + 1 - 1/i}\right) \end{aligned} \quad (20)$$

where M denotes the codebook of 32 symbols, K is the ratio of signal power in LOS path over the scattered power in non-LOS paths.

Finally, from (1), we know that $\rho(dB) = (LQI - p2)/p1$.

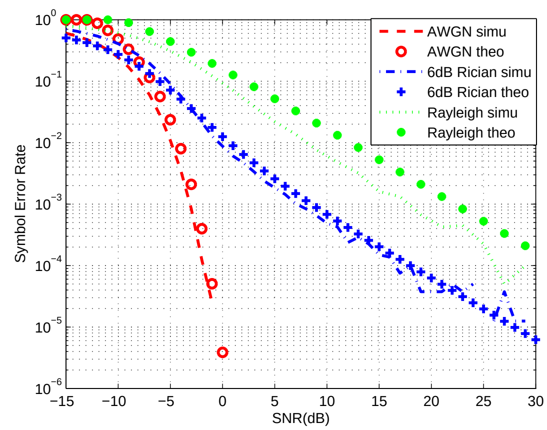

Fig. 5. Zigbee radio SER performance for different channel models

Simulation validation: The simulation setup is similar to the previous section. For each SNR, 10000 packets are sent from TX to RX. We compare the SER performance of the Zigbee radio under different fading channel models, including $AWGN$, Rician fading with $K = 6dB$ and the Rayleigh fading channel. As shown in Figure 5, when the channel condition degrades (from AWGN to Rayleigh), the SER degrades as expected. Furthermore, theoretical and simulation results are quite close. Specifically, for a fixed SER, the prediction error in the Rayleigh channel is around $4dB$.

IV. Experiment Results

To this end, we have developed an analytical model to characterize the SER using LQI for different channel models. Based on (1) and (10), we postulate how LQI is actually computed in terms of the statistical properties of $CORR$. We can describe the relation between LQI measurement and $CORR$ as:

$$LQI = (V - a) * b \tag{21}$$

where $V = 10log_{10}(\frac{\mu_{CORR}^2}{\sigma_{CORR}^2})$, $a = -10log_{10}(\frac{2}{C_{ii}^2}) - \frac{p_2}{p_1}$, $b = p_1$ are the calibration parameters tracked from the empirical experiments.

The field experiments are conducted to validate the analytical models under two different settings, namely, the cabled connection to emulate $AWGN$ channel and an outdoor environment for Rician channels. CH26 is used to avoid the external interferences. In the AWGN channel, we vary the noise levels generated by USRP2 to emulate different SNR conditions. In the outdoor setting, we vary the transmitter's locations while keeping the receiver node fixed, to emulate different fading and shadowing environments. For each transmitter location, 1000 packets are sent from TX to RX. Along with each packet, the LQI, $RSSI$ and SER/PER values are recorded.

Figure 6(a) shows the symbol error rate as a function of SNR in a cabled environment. The predicted SER is computed from LQI based on our analytical model. As shown in the figure, the predicted SER matches well with the inferred SER.

Figure 6(b) shows the results for the outdoor setting. We set the parameters in the analytical model to be $M = 4$ and $K = 12dB^4$. Although the measured SER fluctuates due to fading, the predicted SER is close to the measured value in general. However, in the high SNR region, the predicted SER errors on the higher side. This is mainly because when nodes are very close, the Rician channel model with $M = 4$ and $K = 12dB$ may not suitable any more.

V. Conclusion

In this paper, we utilize both analytical modeling with simulations as well measurement studies to decipher LQI reports from Zigbee radios. The key finding is that LQI is in fact linear with respect to the instantaneous SNR over an appropriate range of SNR values. As a result, LQI can be used to predict SER/PER given the channel models. We believe our study will lead to more informed resource management decisions in Zigbee radio networks.

Acknowledgment

This work was supported by the National Science Foundation (NSF), Grant number CNS-0832084.

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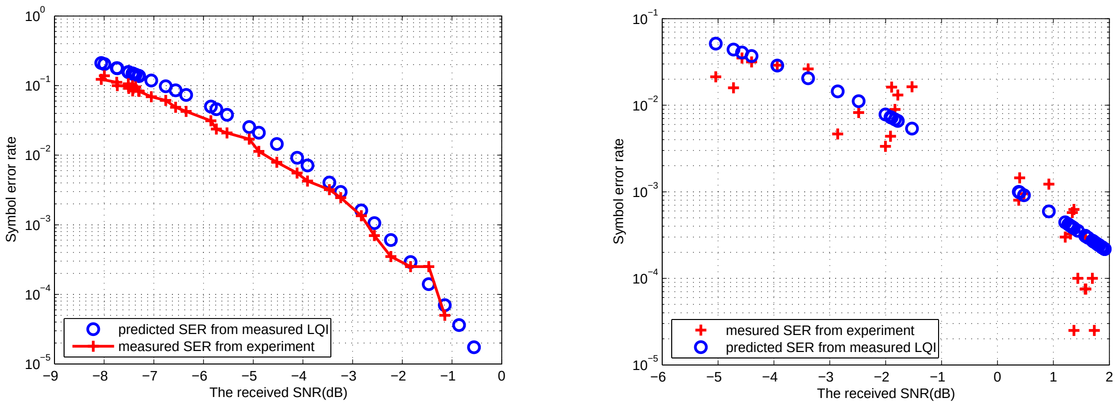
TABLE I
CORRELATION MATRIX OF QUASI-ORTHOGONAL MODULATION

S_i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	32	0	-4	-8	-8	-8	-4	0	0	8	4	-8	-8	-8	4	8
2	0	32	0	-4	-8	-8	-8	-4	8	0	8	4	-8	-8	-8	4
3	-4	0	32	0	-4	-8	-8	-8	4	8	0	8	4	-8	-8	-8
4	-8	-4	0	32	0	-4	-8	-8	-8	4	8	0	8	4	-8	-8
5	-8	-8	-4	0	32	0	-4	-8	-8	-8	4	8	0	8	4	-8
6	-8	-8	-8	-4	0	32	0	-4	-8	-8	-8	4	8	0	8	4
7	-4	-8	-8	-8	-4	0	32	0	4	-8	-8	-8	4	8	0	8
8	0	-4	-8	-8	-8	-4	0	32	8	4	-8	-8	-8	4	8	0
9	0	8	4	-8	-8	-8	4	8	32	0	-4	-8	-8	-8	-4	0
10	8	0	8	4	-8	-8	-8	4	0	32	0	-4	-8	-8	-8	-4
11	4	8	0	8	4	-8	-8	-8	-4	0	32	0	-4	-8	-8	-8
12	-8	4	8	0	8	4	-8	-8	-8	-4	0	32	0	-4	-8	-8
13	-8	-8	4	8	0	8	4	-8	-8	-8	-4	0	32	0	-4	-8
14	-8	-8	-8	4	8	0	8	4	-8	-8	-8	-4	0	32	0	-4
15	4	-8	-8	-8	4	8	0	8	-4	-8	-8	-8	-4	0	32	0
16	8	4	-8	-8	-8	4	8	0	0	-4	-8	-8	-8	-4	0	32

[4]Determination of the Rician channel parameters from measurements will be considered in our future work.



(a) cabled channel environment

(b) outdoor channel environment

Fig. 6. Predicted SER by using LQI in different channel environments