TRANSMIT-POWER REDUCTION FOR CLASS-1 BLUETOOTH-ENABLED INDOOR CORDLESS PHONES

Kun-Wah Yip, *Member, IEEE*, and Tung-Sang Ng, *Senior Member, IEEE*
Department of Electrical and Electronic Engineering
University of Hong Kong, Pokfulam Road, Hong Kong
E-mail: {kwyip,tsng}@eee.hku.hk

Abstract **— Class-1 Bluetooth devices support a transmission range of about 100m and are useful for indoor cordless telephony with advantages of wider coverage, greater user mobility, and more convenience. To minimize the transmit power of class-1 devices, feedback power control specified in the Bluetooth specification can be used. This paper shows that further transmit-power reduction is possible by reducing the *Golden Receive Power Range* (GRPR) from the specified value of 20dB. For typical indoor lognormal-shadowing channels, more than 4dB reduction in the mean transmit power can usually be obtained by reducing the GRPR to 10dB. However, using a smaller GRPR increases the frequency of making power-adjustment requests through the *Link Manager Protocol* (LMP), thereby pre-empting more voice packets and affecting the voice quality. We compute the overhead cost due to power control, defined as the percentage of the total number of packets used for power-adjustment requests, when the GRPR is set at 10dB ± 6dB, wherein 6dB is the tolerance allowed in implementation. It is found that the overhead cost is less than about 1% but becomes close to 1% as the GRPR approaches 4dB, indicating that the link performance would become barely acceptable for voice transmission in some situations. We also consider utilizing the reserved byte in LMP power-control commands to convey the preferred number of power-adjustment steps to the transmitter in order to reduce the overhead cost. With this arrangement, the (worst-case) overhead cost is reduced to about 0.3%, so that the voice quality can be maintained acceptable even if the GRPR is reduced to 10dB ± 6dB for transmit-power reduction.**

Index terms **— Bluetooth, Transmit power, Indoor cordless phones.**

I. INTRODUCTION

Although applications of Bluetooth technology have been primarily focused on short-range communications within 10m, a provision is given in the Bluetooth specification[1] [1] to extend the communication range to about 100m by using a higher transmit power. Bluetooth devices having a maximum output power of 100mW for supporting a 100m transmission range are categorized as power class 1. The extended transmission range is advantageous in the application of class-1 Bluetooth devices for indoor cordless telephony in that the user can be benefited from wider coverage, greater user mobility, and more convenience. Since indoor cordless phones are usually operated by batteries, and the phones are generally used for conversation for a time of minutes or even tens of minutes, minimizing the transmit power while maintaining an acceptable performance is of considerable importance.

Feedback power control specified in the Bluetooth specification [1] can be used to minimize the transmit power of class-1 devices. The specification [1] states that the *Golden Receive Power Range* (GRPR) has a nominal value of 20dB. In this paper, the first objective is to show that further transmit-power reduction is possible by reducing the GRPR. In particular, it is shown that more than 4dB reduction in the mean transmit power can usually be obtained for a lognormal-shadowing channel[2] by lowering the GRPR to 10dB. Despite this merit, using a smaller GRPR has a disadvantage that the frequency of making power-adjustment requests is increased, thereby pre-empting more voice packets for making these requests and thus affecting the voice quality. The second objective of this paper is to characterize and compute the *overhead cost* due to making power-adjustment requests. This overhead cost is defined as the percentage of the total number of packets used for power-adjustment requests. In addition, we investigate if this cost can be reduced by utilizing an unexploited field in the power-control com-

[1] Throughout this paper, we refer to the version 1.1 of the specification.

[2] Lognormal shadowing is commonly encountered in radio propagation inside buildings [2], [3].

Contributed Paper
Manuscript received September 5, 2002

Table 1. Conditions considered for investigation. Corresponding conditions for the current power-control algorithm are also listed.

	Current standard:	Conditions considered for investigation:
GRPR	20dB ± 6dB	15dB ± 6dB (option 1) 10dB ± 6dB (option 2)
n_B	0 (not used)	0, 1, 2, 4, 8
Step size Δ	2dB to 8dB	2dB

Note: n_B is the number of bits in the reserved bytes of the LMP power-control commands used to convey additional information to the transmitter.

mand payload. It is shown that with this arrangement the overhead cost can be made to be less than about 0.3% when the nominal value of GRPR is reduced to 10dB. Since this overhead cost results in a voice-quality degradation that can be considered acceptable for speech transmission, these two results provide positive momentum to use a smaller GRPR for class-1 Bluetooth-enabled indoor cordless phones.[3]

This paper is organized as follows. Section II reviews Bluetooth's power-control algorithm and elaborates the conditions that are considered for investigation. In Section III, analytical results that can be used to compute the mean transmit power and the overhead cost are detailed, where the derivation is given in the Appendix. Impacts of lowering the GRPR on the transmit-power reduction and the overhead cost are discussed in Section IV. Finally, Section V concludes the paper.

II. Review of Power-Control Algorithm, and Conditions for Investigation

The power-control algorithm [1] is reviewed as follows. At the receiver, the received signal strength in dBm, J_r, is measured by the *Receiver Signal Strength Indicator* (RSSI) and compared against the lower and upper threshold levels in dBm, denoted by $J_r^{(\mathrm{LT})}$ and $J_r^{(\mathrm{UT})}$, respectively. The lower threshold level specifies the minimum power level that yields an acceptable performance. If J_r is lower than $J_r^{(\mathrm{LT})}$, a request to increase the transmit power by Δ dB is sent from the receiver to the transmitter. If J_r is higher than $J_r^{(\mathrm{UT})}$, a request to decrease the transmit power by Δ dB is issued. The request to increase or decrease the transmit power is communicated to the transmitter through the *Link Manager Protocol* (LMP). LMP commands of `LMP_decr_power_req` and `LMP_incr_power_req` are sent to request a decrease and increase, respectively, of the transmit power. Currently, the content field in each of these LMP commands is assigned with one byte, which is reserved for future use so that its value is not yet defined. Note that in sending a LMP command, a time slot is occupied, correspondingly causing a loss of a voice packet. The specification [1] also states that the allowable step size Δ ranges from 2dB to 8dB and the GRPR, defined by $J_r^{(\mathrm{UT})} - J_r^{(\mathrm{LT})}$, has a nominal size of 20dB with an accuracy of ±6dB.

The conditions of interest that we consider for investigation are summarized in Table 1. The corresponding ones for the current Bluetooth standard [1] are also listed for reference. We consider two sets of GRPR recommendations, namely, 15dB ± 6dB and 10dB ± 6dB, wherein the ±6dB is the GRPR accuracy (or tolerance allowed in practical implementation), and the figures 15dB and 10dB are nominal values under consideration. Note that the GRPR accuracy considered here is the same as the one used in the current specification. We also consider utilizing the reserved byte in the content field of the LMP commands `LMP_decr_power_req` and `LMP_incr_power_req`. It is assumed that n_B bits in the reserved byte are used to indicate that it is preferred to increase or decrease the transmit power by $N_B\Delta$ dB, where N_B ($1 \le N_B \le 2^{n_B}$) is the value contained in the n_B bits.[4] It is apparent that this arrangement can reduce the number of LMP commands made to request power adjustment so that the overhead cost can be decreased. Notice that in the special case of $n_B = 0$, the reserved byte

[3] Note that a revision of the Bluetooth specification is required.

[4] The specification also mentions that the reserved byte could be used in a similar manner in the future [1, pp. 223], although currently its use is not yet defined.

is not used and this case reduces to the one for the current Bluetooth system. Also note that it is not necessary to use different values of step size Δ to speed up the convergence. Therefore, we consider only the case that Δ = 2dB.

III. Analytical Results

We assume that power control is used to compensate for the path loss and shadowing but not for fast fading. In Bluetooth systems, fast fading can be more easily compensated for by frequency hopping. The *mean* received power J_r, obtained by averaging the received power measured over a sufficient number of frequency hops, is then used to determine if an increase or decrease of transmit power is required. Lognormal shadowing is considered. The shadowing depth, viz., the dB standard deviation of lognormal shadowing, is denoted by σ_{dB}. In indoor communications, typical values of σ_{dB} range from 3dB to 6dB [2].

The power-control algorithm can be modeled by a Markov chain. Its analysis is given in the Appendix. It is found that for σ_{dB} within 3dB and 6dB, a unique solution of the stationary state probabilities can be obtained, indicating that an equilibrium independent of initial conditions (i.e., initial setting of transmit power) is reached. The stationary state probabilities are used to compute the mean transmit power and the overhead cost. In the Appendix, it is shown that the dB value of mean transmit power ($\overline{W_t}$) above the minimum one required in the absence of shadowing ($W_t^{(\min)}$), A_{dB}, is given by

$$A_{\text{dB}} = 10\log_{10}\frac{\overline{W_t}}{W_t^{(\min)}} = 10\log_{10}\left(\int_0^1 \sum_{i=-M'}^{M} P_i(\xi)\times 10^{(i+\xi)\Delta/10}d\xi\right) \qquad (1)$$

where $P_i(\xi)$ is the stationary state probability, conditioned on ξ, for the state i, and M and M' are given by (14) and (15), respectively, in the Appendix. We mention that $W_t^{(\min)}$ is independent of the choice of GRPR (see Appendix), so that comparison among A_{dB} values for different GRPRs is indicative to the transmit-power reduction achieved for a given GRPR with respect to the reference GRPR of 20dB, which is currently adopted in the specification [1]. It is also shown that the mean number of LMP power-control commands required in response to a channel change due to shadowing, $\overline{N}$, is computed by

$$\overline{N} = \int_0^1 \sum_{i=-M'}^{M} P_i(\xi) \times\left\{\sum_{n=1}^{M-i} p_{i,i+n}\left\lceil n/2^{n_B}\right\rceil + \sum_{n=1}^{M'+i} p_{i,i-n}\left\lceil n/2^{n_B}\right\rceil\right\}d\xi \qquad (2)$$

where $p_{i,i'}$, given by (16) in the Appendix, is the transition probability from state i to state i', and $\lceil\cdot\rceil$ is the ceiling function. Let T_{coh} be the coherence time of lognormal shadowing, and assume that the channel changes as a result of shadowing after a time of T_{coh}. The overhead cost, C_{pc}, can be estimated by

$$C_{pc} = \frac{\overline{N}}{T_{coh}/T_{pr}}\times 100\% \qquad (3)$$

where $1/T_{pr}$ is the packet repetition rate of the Bluetooth device.

Measurement results of [3] have shown that the normalized correlation of shadowed components observed in indoor communications drops to 0.5 at a distance of approximately 2m. Making a reasonable assumption that the Bluetooth device used inside buildings moves at a speed of at most 2ms^{-1}, we consider that T_{coh} = 1s in the computation of C_{pc}, giving a worst-case value in the overhead cost. For voice transmission in Bluetooth systems, synchronous connection oriented (SCO) links are used. Since the maximum number of SCO links that can be supported in a piconet is three, we consider the situation that three SCO links can be established (giving the largest T_{pr} and hence resulting in the worst-case overhead cost). It follows that T_{pr} = 625μs × 2 × 3 = 3.7ms.

We should mention that the computed values of A_{dB} and C_{pc} can be affected by the choice of M and M', which depends on the maximum ($J_{t,\max}$) and minimum ($J_{t,\min}$) output power levels of the Bluetooth device as seen from (14) and (15). Since our objective is to investigate the effects of different GRPRs rather than the variation of $J_{t,\max}$ or $J_{t,\min}$ on the transmit power and overhead cost, we consider the case that $J_{t,\max}$ and $J_{t,\min}$, respectively, are sufficiently high and low such that their effects on A_{dB} and C_{pc} are negligible. In the computation of numerical results that follow, we use $J_{t,\max} = J_t^{(\min)}$ + 40dBm and $J_{t,\min} = J_t^{(\min)}$ – 20dBm to compute M and M' by (14) and (15).

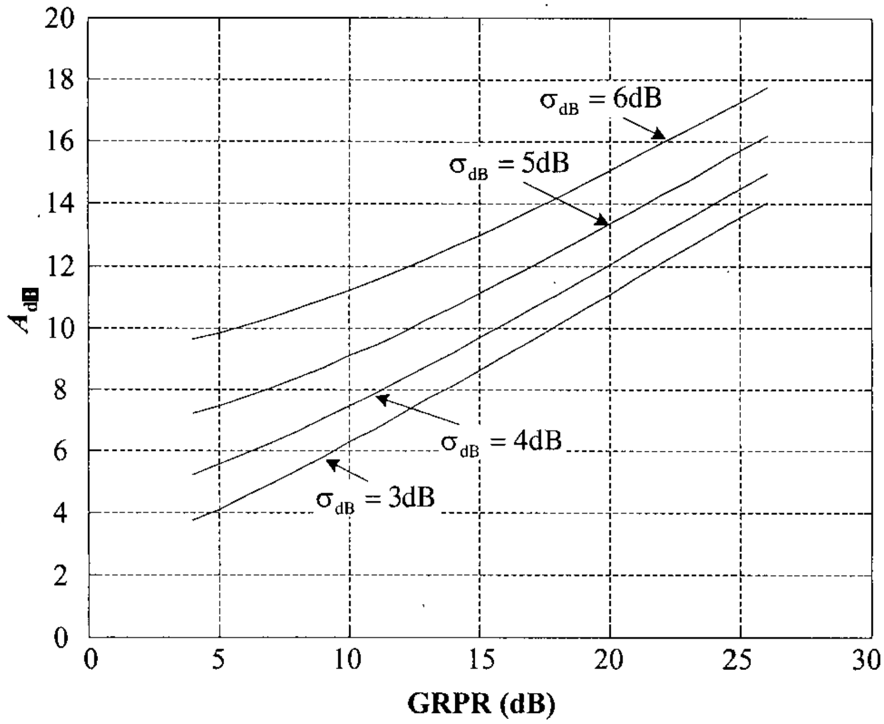

Fig. 1. A_{dB} (dB value of mean transmit power above the minimum required power) against GRPR for different shadowing depth σ_{dB}.

Table 2. Transmit-power reduction for GRPR = 10dB and 15dB.

	Transmit-Power Reduction (dB)	
	GRPR = 10dB	GRPR = 15dB
σ_{dB} = 3dB	4.82	2.44
σ_{dB} = 4dB	4.58	2.36
σ_{dB} = 5dB	4.25	2.23
σ_{dB} = 6dB	3.84	2.06

IV. Numerical Results and Discussion

A. *Transmit-Power Reduction*

Fig. 1 plots the A_{dB} values against GRPR (4dB – 26dB) for different σ_{dB} ranging from 3dB to 6dB. Note that the range of 4dB to 26dB for GRPR covers the cases we are interested in, i.e., GRPRs of 20dB±6dB, 15dB±6dB and 10dB±6dB. It is apparent that a smaller GRPR yields a lower A_{dB}, indicating that the required mean transmit power is decreased by reducing the GRPR. The rate of reduction in mean transmit power is about 0.45dB per one dB reduction in the GRPR. Table 2 lists the transmit-power reduction for different σ_{dB} when a GRPR of 10dB or 15dB is used instead of 20dB, wherein the transmit-power reduction is computed as the difference of the A_{dB} values for the case of GRPR = 20dB and the other case that is considered. When GRPR = 15dB, only a modest reduction of about 2dB in the mean transmit power is obtained. A greater reduction of more than 4dB in most cases of σ_{dB} can be achieved if the GRPR is reduced to 10dB. This reduction is quite substantial. In addition, since it is more than 3dB, it leads to a possibility of doubling the battery support life for indoor cordless phones. Therefore, we focus our interest on the case that the GRPR is set at a nominal value of 10dB with an accuracy of ±6dB.

B. *Selection of n_B*

Table 3 lists the values of $\overline{N}$ for GRPRs of 10dB and 20dB against different values of σ_{dB} and n_B. As expected, more power-adjustment requests are required if the GRPR is reduced from 20dB to 10dB, and a higher number of requests are needed when the channel is subjected to more severe shadowing (with a higher σ_{dB}). It is also apparent that for a given selection of σ_{dB} and GRPR, the value of $\overline{N}$ in a case of non-zero n_B is always lower than the one in the case that n_B = 0. This result demonstrates that transmitting the preferred number of steps for power adjustment is effective to reduce the

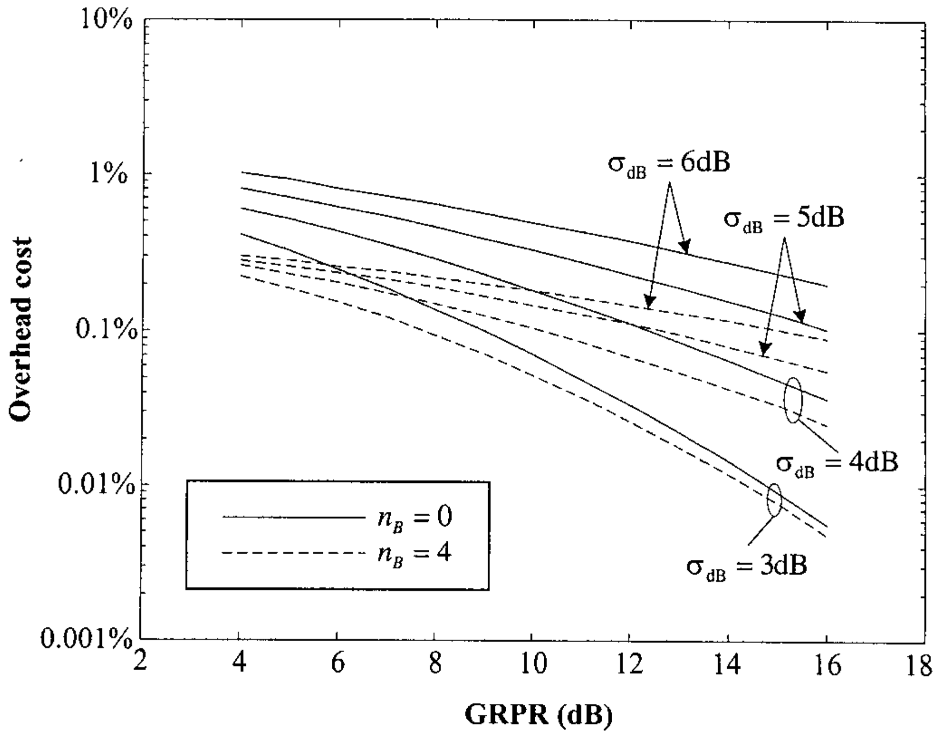

Fig. 2. Overhead cost against GRPR for different n_B and σ_{dB}.

number of LMP commands to be sent, implying that the overhead cost for power control can be reduced. However, the improvement in $\overline{N}$ diminishes as n_B increases. In particular, results listed in Table 3 show that using n_B = 8 yields no improvement over using n_B = 4. This observation indicates that it is sufficient to use only four bits in the reserved byte to encode the preferred number of steps, whereas using a higher number of bits is not effective to further reduce the overhead cost due to power control.

C. Overhead Cost due to Power Control

Since the overhead cost is a result of data packets being used for power-adjustment requests rather than for voice transmission, it can be interpreted in a manner similar to the outage probability. (Outage is an event that the link is not unusable due to unacceptable link performance.) For voice transmission, the outage probability is usually set at 1% [4], [5]. Therefore, we consider a overhead cost of 1% as a reference above which the link performance is considered unsatisfactory. Fig. 2 plots the values of C_{pc} against GRPR from 4dB to 16dB for $n_B \in \{0, 4\}$ and $\sigma_{\mathrm{dB}} \in$ {3dB, 4dB, 5dB, 6dB}. Consider first the case that the reserved byte is not used, i.e., n_B = 0. It is apparent that although the overhead cost is less than about 1% over the entire range of GRPR under consideration and for all cases of σ_{dB}, the value of C_{pc} at

Table 3. Values of $\overline{N}$ for GRPRs of (a) 20dB and (b) 10dB.

(a) GRPR = 20dB

σ_{dB}	$\overline{N}$ $n_B = 0$	$n_B = 1$	$n_B = 2$	$n_B = 4$	$n_B = 8$
3dB	0.0017	0.0016	0.0016	0.0016	0.0016
4dB	0.0256	0.0204	0.0193	0.0192	0.0192
5dB	0.1071	0.0763	0.0661	0.0651	0.0651
6dB	0.2622	0.1730	0.1370	0.1300	0.1300

(b) GRPR = 10dB

σ_{dB}	$\overline{N}$ $n_B = 0$	$n_B = 1$	$n_B = 2$	$n_B = 4$	$n_B = 8$
3dB	0.1889	0.1480	0.1395	0.1394	0.1394
4dB	0.4898	0.3381	0.2842	0.2784	0.2784
5dB	0.8767	0.5603	0.4255	0.3949	0.3949
6dB	1.3151	0.8002	0.5645	0.4850	0.4850

σ_{dB} = 6dB is close to 1% as the GRPR approaches 4dB. It follows that if a GRPR of 10dB ± 6dB be used in Bluetooth-enabled indoor cordless phones, the link performance might become barely acceptable in some situations. The overhead cost can be reduced by utilizing the reserved byte in the LMP power-control commands. In the case of n_B = 4, it is apparent that C_{pc} can be reduced to be less than about 0.3%. This improvement enables class-

1 Bluetooth equipment for indoor cordless telephony to achieve better voice quality and more-robust link performance.

V. Conclusions

We have shown that the mean transmit power of class-1 Bluetooth devices for indoor cordless telephony can be further reduced by using a GRPR smaller than 20dB, the nominal value specified in the current specification. In addition, it has been found that more than 4dB reduction in the mean transmit power can usually be obtained if the GRPR is lowered from 20dB to 10dB. This advantage of further transmit-power reduction has motivated us to investigate the overhead cost for power control if the GRPR is set at a nominal value of 10dB with a tolerance of ±6dB. If the reserved byte in the LMP power-control command is not used, numerical results have shown that the overhead cost is less than about 1% but it becomes close to 1% as the GRPR approaches 4dB, the lower limit in the allowable range of GRPR. In some situations, the link performance might be barely acceptable for voice transmission. Using the reserved byte to include the preferred number of power-adjustment steps in a LMP command allows a reduction of the overhead cost. Numerical results have shown that one only needs to use four bits in the reserved byte to encode the number of steps, and using more bits is not effective to further reduce the overhead cost. For the case of using four bits, the (worst-case) overhead cost is reduced to about 0.3%. With this arrangement of utilizing the reserved byte in the LMP power-control command, and by lowering the GRPR from 20dB to 10dB, the mean transmit power can be reduced while the voice quality can be maintained to be acceptable.

Appendix. Markov Analysis of the Power-Control Algorithm

In the presence of lognormal shadowing, the mean received power in dBm is given by

$$J_r = J_t + 10\log_{10} G \tag{4}$$

where J_t is the transmit power in dBm, and G is the channel gain modeled by a lognormal random variable. Let μ_{dB} and σ_{dB} be the mean and standard deviation, respectively, of $10\log_{10} G$. It follows that

$$J_r = J_t + \mu_{\text{dB}} + \sigma_{\text{dB}} U \tag{5}$$

where U is a standard normal random variable. The mean channel gain, $\overline{G}$, is given by [6]

$$\overline{G} = e^{\gamma\mu_{\text{dB}} + \frac{1}{2}\gamma^2\sigma_{\text{dB}}^2} \tag{6}$$

where $\gamma = (\ln 10)/10$ is a scale factor. In the absence of lognormal shadowing, the minimum transmit power in mW required to achieve an acceptable performance, $W_t^{(\min)}$, is computed by

$$W_t^{(\min)} = \overline{G}^{-1} 10^{J_r^{(\text{LT})}/10}. \tag{7}$$

Note that $W_t^{(\min)}$ is independent of the choice of GRPR. We wish to compute the mean transmit power in the presence of shadowing, $\overline{W_t}$, and compare it to $W_t^{(\min)}$. That is, we evaluate

$$A_{\text{dB}} = 10\log_{10}\frac{\overline{W_t}}{W_t^{(\min)}} \quad [\text{dB}]. \tag{8}$$

Consider a Markov model with states numbered from $-M'$ to M where M' and M are to be determined. Let

$$\begin{aligned} J_t^{(\min)} &= 10\log_{10} W_t^{(\min)} \\ &= J_r^{(\text{LT})} - \mu_{\text{dB}} - \gamma\sigma_{\text{dB}}^2/2 \quad [\text{dBm}]. \end{aligned} \tag{9}$$

The state i refers to the case that J_t is in the range $J_t \in \mathrm{H}_i$, where

$$\mathrm{H}_i = \left[J_t^{(\min)} + i\Delta, J_t^{(\min)} + (i+1)\Delta\right), \quad -M' \le i \le M. \tag{10}$$

Let

$$\mathrm{F}_n = \left[J_r^{(\text{UT})} + (n-1)\Delta, J_r^{(\text{UT})} + n\Delta\right), \quad n \ge 1, \tag{11}$$

and

$$\mathrm{G}_n = \left[J_r^{(\text{LT})} - n\Delta, J_r^{(\text{LT})} - (n-1)\Delta\right), \quad n \ge 1. \tag{12}$$

Assume that the shadowing is slowly varying such that the power-control mechanism can successfully respond to it. If $J_r \in \mathrm{G}_n$, the power-control algorithm drives the transmit power to increase by $n\Delta$ dB in order that the adjusted J_r is within $J_r^{(\text{LT})}$ and $J_r^{(\text{UT})}$. It follows that the system is transited from the state i to the state $i+n$ unless the transmit power reaches the maximum. In this case, the system reaches the terminating state, i.e., the state M. Thus, M can be determined from the maximum output power of a Bluetooth device. Similar reasoning applies if $J_r \in \mathrm{F}_n$. Let $J_{t,\max}$ and $J_{t,\min}$ be the maximum and minimum output power levels in dBm, respectively, of the Bluetooth device under consideration. It is possible to express J_t as

$$J_t = J_t^{(\min)} + (i+\xi)\Delta \tag{13}$$

in which $\xi \in [0,1)$. Since $J_{t,\min} \le J_t \le J_{t,\max}$, we have that

$$M = \left\lfloor -\xi + (J_{t,\max} - J_t^{(\min)})/\Delta \right\rfloor \quad (14)$$

and

$$M' = \left\lfloor \xi - (J_{t,\min} - J_t^{(\min)})/\Delta \right\rfloor \quad (15)$$

where $\lfloor x \rfloor$ is the integer less than or equal to x. Let $p_{i,i'}$ be the transition probability of state i entering into state i'. It follows that

$$p_{i,i+n} = \Pr\left\{J_r \in \mathrm{G}_n \middle| J_t \in \mathrm{H}_i\right\}, \quad 1 \le n \le M - i - 1, \quad \textbf{(16a)}$$

$$p_{i,i-n} = \Pr\left\{J_r \in \mathrm{F}_n \middle| J_t \in \mathrm{H}_i\right\}, \quad 1 \le n \le M' + i - 1, \quad \textbf{(16b)}$$

$$p_{i,M} = \Pr\left\{J_r \in \textstyle\bigcup_{n=M-i}^{\infty} \mathrm{G}_n \middle| J_t \in \mathrm{H}_i\right\}, \quad i \ne M, \quad \textbf{(16c)}$$

$$p_{i,-M'} = \Pr\left\{J_r \in \textstyle\bigcup_{n=M'+i}^{\infty} \mathrm{F}_n \middle| J_t \in \mathrm{H}_i\right\}, \quad i \ne -M', \quad \textbf{(16d)}$$

$$p_{i,i} = 1 - \textstyle\sum_{i'=-M', i' \ne i}^{M} p_{i,i'} . \quad \textbf{(16e)}$$

Substituting (5), (9) and (13) into (16a)-(16d) yields

$$p_{i,i+n} = Q\left(\frac{1}{2}\gamma\sigma_{\mathrm{dB}} - \frac{n+i+\xi}{\sigma_{\mathrm{dB}}/\Delta}\right) - Q\left(\frac{1}{2}\gamma\sigma_{\mathrm{dB}} - \frac{n-1+i+\xi}{\sigma_{\mathrm{dB}}/\Delta}\right), \quad 1 \le n \le M - i - 1, \quad \textbf{(17a)}$$

$$p_{i,i-n} = Q\left(\frac{1}{2}\gamma\sigma_{\mathrm{dB}} + \frac{n-1+S-i-\xi}{\sigma_{\mathrm{dB}}/\Delta}\right) - Q\left(\frac{1}{2}\gamma\sigma_{\mathrm{dB}} + \frac{n+S-i-\xi}{\sigma_{\mathrm{dB}}/\Delta}\right), \quad 1 \le n \le M' + i - 1, \quad \textbf{(17b)}$$

$$p_{i,M} = 1 - Q\left(\frac{1}{2}\gamma\sigma_{\mathrm{dB}} - \frac{M-1+\xi}{\sigma_{\mathrm{dB}}/\Delta}\right), \quad i \ne M, \quad \textbf{(17c)}$$

$$p_{i,-M'} = Q\left(\frac{1}{2}\gamma\sigma_{\mathrm{dB}} + \frac{M'-1+S+\xi}{\sigma_{\mathrm{dB}}/\Delta}\right), \quad i \ne -M', \quad \textbf{(17d)}$$

where $Q(x) = (2\pi)^{-1/2}\int_x^{\infty} e^{-t^2/2}dt$ is the tail probability of the standard normal distribution, and

$$S = (J_r^{(\mathrm{UT})} - J_r^{(\mathrm{LT})})/\Delta . \quad \textbf{(18)}$$

The transition matrix, $\mathbf{T}_\xi$, is a function of ξ and is given by $\mathbf{T}_\xi = [p_{i,i'}]_{i,i'=-M',\cdots,M}$. Let $P_i(\xi)$, conditioned on ξ, be the stationary probability of the state i, and denote $\mathbf{P}_\xi = [P_{-M'}(\xi), \ldots, P_M(\xi)]$ as the state-probability vector. Note that $\mathbf{P}_\xi$ characterizes the distribution of transmit power. It is known [7] that $\mathbf{P}_\xi$, if exists, is an eigenvector of $\mathbf{T}_\xi$ with the corresponding eigenvalue equal to 1 and with $\sum_{i=-M'}^{M} P_i(\xi) = 1$. It is possible that $\mathbf{T}_\xi$ has multiple unity eigenvalues. In such case the distribution is not unique. We find that this situation occurs when σ_{dB} is too low (less than 2dB). This situation is not dealt with in this paper as the range of σ_{dB} of interest is 3dB-6dB. Note that the uniqueness and existence of $\mathbf{P}_\xi$ implies that the distribution of transmit power is independent of the level of initial transmit power.

We model that ξ is a uniform random variable over [0,1). This assumption is made in order to compute representative values of mean transmit power and mean number of power-adjustment requests for different Bluetooth devices, which may have different initial transmit power and hence different ξ. The mean transmit power in mW is given by $\overline{W_t} = E\{10^{J_t/10}\}$ wherein J_t is given by (13) and the expectation is taken over all the states and the random variable ξ. Evaluating $\overline{W_t}$ and substituting the resultant expression into (8), we get

$$A_{\mathrm{dB}} = 10\log_{10}\left(\int_0^1 \sum_{i=-M'}^{M} P_i(\xi) \times 10^{(i+\xi)\Delta/10} d\xi\right). \quad \textbf{(19)}$$

The integral can be easily computed by a numerical technique such as Simpson's rule. The mean number of power-adjustment requests (LMP commands), denoted by $\overline{N}$, is computed by noting that when the state i is transited to the state $i \pm n$, the number of power-adjustment requests made is $\lceil n/2^{n_B} \rceil$ where $\lceil \cdot \rceil$ is the ceiling function. It follows that

$$\overline{N} = \int_0^1 \sum_{i=-M'}^{M} P_i(\xi) \times \left\{ \sum_{n=1}^{M-i} p_{i,i+n} \cdot \left\lceil n/2^{n_B} \right\rceil + \sum_{n=1}^{M'+i} p_{i,i-n} \cdot \left\lceil n/2^{n_B} \right\rceil \right\} d\xi. \quad \textbf{(20)}$$

In the derivation of (20), we make use of the simplifying assumption that when the system is transited to an end state (state M or state M'), the extra LMP command that requests the transmit power to go beyond $J_t^{(\max)}$ or $J_t^{(\min)}$ has a negligible effect on the resultant $\overline{N}$.

REFERENCES

[1] Bluetooth SIG, *Specification of the Bluetooth System: Core*, v. 1.1, Feb. 22, 2001.

[2] G. Hess and M. Marsan, "Operational characteristic of transportable in-building propagation," *Proc. IEEE GLOBECOM'94*, pp. 37-41, Nov. 28 - Dec. 2, 1994.

[3] J. C. Liberti and T. S. Rappaport, "Statistics of shadowing in indoor radio channels at 900 and 1900 MHz," *Proc. IEEE MILCOM'92*, pp. 1066-1070, Oct. 11-14, 1992.

[4] M.-H. Fong and V. K. Bhargava, "Efficient integration of multi-rate traffic for 3rd generation DS-CDMA systems," *Proc. IEEE ICC'99*, pp. 1426-1430, Jun. 6-10, 1999.

[5] K. S. Gilhousen, I. M. Jacobs, R. Padovani, A. J. Viterbi, L. A. Weaver, Jr., C. E. Wheatley III, "On the capacity of a cellular CDMA system," *IEEE Trans. Veh. Technol.*, vol. 40, pp. 303-312, May 1990.

[6] E. L. Crow and K. Shimizu (ed.), *Lognormal Distributions: Theory and Applications*, New York: Marcel Dekker, 1988, p. 9.

[7] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*, 3rd ed., New York: McGraw-Hill, 1991, p. 639.

AUTHORS' BIOGRAPHIES

Kun-Wah Yip (M'96) received the B.Eng. (Hons) and Ph.D. degrees in electrical engineering from The University of Bradford, UK, in 1991 and The University of Hong Kong in 1995, respectively.

From 1995 to 1998, he was a research associate and then a postdoctoral fellow at The University of Hong Kong. Currently, he is a research assistant professor at the same university. His research interest is on WLANs, WPANs, communication circuits, spread-spectrum techniques, OFDM, and efficient simulation techniques for communication systems.

Tung-Sang Ng (S'74-M'78-SM'90) received the B.Sc.(Eng.) degree from the University of Hong Kong in 1972, and the M.Eng.Sc. and Ph.D. degrees from the University of Newcastle, Australia, in 1974 and 1977, respectively, all in electrical engineering.

He worked for BHP Steel International and The University of Wollongong, Australia, after graduation for 14 years and returned to Hong Kong in 1991, taking up the position of Professor and Chair of Electronic Engineering. He is Head of Department of Electrical and Electronic Engineering since 2000. His current research interests include wireless communication systems, spread spectrum techniques, CDMA and digital signal processing. He was the General Chair of ISCAS'97 and the VP-Region 10 of IEEE CAS Society (1999 & 2000). He was an Executive Committee Member and a Board Member of the IEE Informatics Divisional Board (1999-2001) and was an ordinary member of IEE Council (1999-2001). He has published over 170 International journal and conference papers.

He was awarded the Honorary Doctor of Engineering Degree by the University of Newcastle, Australia in August, 1997 for his services to higher education generally and to engineering education specifically. He received the Senior Croucher Foundation Fellowship in 1999 and the IEEE Millenium medal in February, 2000.

He is a Fellow of the IEE, HKIE and a Senior Member of IEEE.