Effect of Narrowband Channels on the Control Performance of a Mobile Sensor Node

Yasamin Mostofi (yasi@caltech.edu)   Richard Murray (murray@caltech.edu)

California Institute of Technology, Pasadena, CA 91125, USA

Abstract— In mobile sensor networks, sensor measurements as well as control commands are transmitted over wireless time-varying links. It then becomes considerably important to address the impact of imperfect communication on the overall performance. In this paper, we study the effect of time-varying communication links on the control performance of a mobile sensor node. In particular, we investigate the impact of fading. We derive key performance measure parameters to evaluate the overall feedback control performance over narrowband channels. We show that fading can result in considerable delay and/or poor performance of the mobile sensor depending on the system requirements. To improve the performance, we then show how the application layer can use the channel status information of the physical layer to adapt control commands accordingly. We show that sharing information across layers can improve the overall performance considerably. We verify our analytical results by simulating a wireless speed control problem.

I. INTRODUCTION

There have recently been considerable interest in sensor networks [1], [2]. Such networks have a wide range of applications such as environmental monitoring, surveillance, security, smart homes and factories, target tracking and military. To address and overcome technological challenges of such networks, different and non-traditional designs and strategies should be used. Such designs lie at the intersection of multiple disciplines like control, communication, computation and processing necessitating cross-disciplinary approaches.

Communication plays a key role in the overall performance of sensor networks as sensor measurements and control commands are transmitted over wireless links. Most of the research on the impact of communication on sensor networks focuses on fixed wireless scenarios. Furthermore while impacts of some aspects

of a communication link like noise, quantization, delay and medium access have been addressed to some extent [3], [4], [5], [6], impact of channel fading on mobile sensor networks and utilizing channel status information in application layer have not been studied. In this paper we investigate the impact of narrowband channels on the control performance of a mobile sensor node. We consider the scenarios where a sensor and an actuator are mounted on a mobile unit that is controlled wirelessly by a distant unit. To evaluate the overall feedback control performance, we derive key performance measure parameters. We show that fading can degrade the control performance considerably. To improve the performance we propose a control algorithm that adapts to the quality of the channel. We show that the algorithm can improve the performance considerably. Finally simulation results confirm the mathematical analysis.

II. SYSTEM MODEL

A. Dynamics of the mobile node

Consider a mobile node equipped with a sensor and an actuator with the following linear dynamics:

$$\frac{dx(t)}{dt} = Fx(t) + Gu(t)$$
$$y(t) = x(t),$$
(1)

where x, y, and u represent the state, output and input of the mobile node respectively. We assume scalar quantities for simplicity. After sampling, the discrete model will be as follows:

$$x(k+1) = \phi x(k) + \gamma u(k)$$
$$y(k) = x(k)$$
$$\phi = e^{FT}$$
$$\gamma = \frac{G}{F}(\phi - 1),$$
(2)

where T represents the sampling period. The mobile node transmits its measurement, y, to a distant controller every T seconds. The controller makes an estimate of the transmitted data based on its reception and applies the control signal:

$$u(k) = -\alpha \times \hat{y}(k),$$
(3)

where $\hat{y}(k)$ is the controller estimate of the kth sensor measurement. In this paper we are only considering the effect of imperfect communication on the reception of the sensor measurements at the controller (Eq. 3) to facilitate mathematical derivations. Including the effect of imperfect reception of the control commands at the mobile node would further highlight the results derived in this paper. Without loss of generality, we assume that the goal of the controller is to drive the output of the mobile node, y, to zero. parameter α in Eq. 3 represents controller coefficient and is assumed fixed for now. In Section V we will show how to adapt α to the quality of the communication link. We assume that the controller is fixed in location. The results can be easily extended to

the case of a mobile controller by changing the channel model to include effect of double mobility [7].

B. Communication Channel

Fig. 1 shows the baseband equivalent wireless communication link from the mobile sensor to the controller. At each sampling time instant, y will be quantized and modulated at the mobile sensor. The controller would receive, $\hat{y}(k)$, a corrupted version of y after processing the received data point. After quantization we will have:

$$y(k) = y_q(k) + w_q(k), \qquad (4)$$

where $y_q(k)$ and $w_q(k)$ represent the output of the quantizer and quantization noise respectively. In this paper we consider BPSK modulation[1]. Let $y_p^k(t)$ represent the input to the channel at k^{th} transmission. This gives,

$$y_p^k(t) = \sum_{i=0}^{N_b-1} b_i^k P(t - iT_b - kT)$$
$$for \quad kT \leq t \leq kT + T_b N_b, \qquad (5)$$

where N_b represents the number of bits per transmission, T_b is the pulse duration, b_i^k denotes the ith bit of the kth transmission and $P(t)$ is the pulse shaper. At the output of the channel we will have,

$$y_o^k(t) = \sum_{i=0}^{N_b-1} h_i^k b_i^k P(t - iT_b - kT - T_d^k) + n^k(t)$$
$$for \quad kT + T_d^k \leq t \leq kT + T_d^k + T_b N_b, \qquad (6)$$

[1]Extending the analysis to other modulations should be a straight forward extension of the work presented here.

where T_d^k represents the delay between the kth transmission and the corresponding reception and $n^k(t)$ is AWGN. h_i^k represents the value of the baseband equivalent channel at i^{th} bit of the kth transmission. We consider narrowband channels in this paper. Note that channel may be time-varying during one transmission as can be seen from Eq. 6. After sampling the received signal, we will have,

$$y_o^k(i) = h_i^k b_i^k + n^k(i) \quad for \quad 0 \leq i \leq N_b - 1. \qquad (7)$$

Finally the controller makes an estimate of the transmitted sensor measurement:

$$\hat{y}(k) = y(k) + \underbrace{w_q(k) + w_c(k)}_{w(k)}, \qquad (8)$$

where $\hat{y}(k)$ represents the estimated sensor measurement, $w_c(k)$ is the communication noise ($w_c(k)$ includes the effect of fading and AWGN) and $w_q(k)$ is as defined in Eq. 4.

III. KEY PERFORMANCE MEASURE PARAMETERS

It is the goal of this section to address the impact of imperfect communication and its dynamics on the overall control performance analytically. We will derive key performance measure parameters to describe and understand the impact of physical layer parameters on the application layer. Imperfect communication can ruin the overall control performance by introducing

divergence, delay in convergence and/or an asymptotic error floor. We will find the following key performance measure parameters to evaluate the performance:

1) $E(y^2(k))$ which is the average square error (averaged over the distribution of channel and noise) at k^{th} time instant. Smaller $E(y^2(k))$ indicates better performance.

2) $P_{Thresh}(k) = Prob\{|y(k)| > Threshold\}$ which represents 1-cdf of $|y(k)|$. $E(y^2(k))$ is easier to measure but only provides an average measure of performance while $P_{Thresh}(k)$ demonstrates complete dynamics of $|y(k)|$.

A. Deriving $E(y^2(k))$:

Using Eq. 2, 3 and 8, we will have:

$$y(k) = \beta^k y(0) - \underbrace{\gamma\alpha \sum_{i=1}^{k} \beta^{i-1} w(k-i)}_{z(k)}, \qquad (9)$$

where $w(k)$ is as marked in Eq. 8 and $\beta = \phi - \gamma\alpha$. In the ideal case of perfect communication, $y(k)$ would have exponentially decayed towards zero, the desirable output. This is not the case any more in the presence of imperfect communication. Using Eq. 9, we have,

$$E(y^2(k)) = \beta^{2k} y^2(0) + \\ \gamma^2\alpha^2 \sum_{i=1}^{k} \sum_{i'=1}^{k} \beta^{i+i'-2} \overline{w(k-i)w(k-i')}, \qquad (10)$$

where

$$\overline{w(i)w(i')} = \overline{w_c(i)w_c(i')} + \overline{w_q(i)w_q(i')} \qquad (11)$$

since the communication and quantization noises (w_c and w_q) are independent. As the quantization noise typically gets relatively smaller values than the communication noise, we assume that w_qs are uncorrelated: $\overline{w_q(i)w_q(i')} = 0$ for $i \neq i'$ to reduce the complexity of the analysis. We will see in Section IV that the results derived under this assumption can predict the true performance of the system considerably well. There we will discuss the effect of correlated quantization noise in more details. Next we derive the statistics of w_c. Consider the channel realization over the kth transmission: $\vec{h}^k = [h_0^k h_1^k \ldots h_{N_b-1}^k]$. Then $w_c(k)$ will have the following *pdf* [8]:

$$w_c(k) = \begin{cases} \pm 2^i \times \Delta & with \quad prob. \quad of \quad P_{b,N_b-1-i}^k \\ & \quad for \quad 0 \leq i \leq N_b - 1 \\ \\ 0 & with \quad prob. \quad of \quad 1 - \sum_{i=0}^{N_b-1} P_{b,i}^k \end{cases} \qquad (12)$$

where $P_{b,i}^k$ is the instantaneous bit error probability of the ith bit of the kth transmission[2] and Δ is the quantizer step size. We will have:

$$E(w_c^2(k)|\vec{h}^k) = \Delta^2 \sum_{i=0}^{N_b-1} 2^{2i} P_{b,N_b-1-i}^k. \qquad (13)$$

[2]Eq. 12 is derived under the assumption that the probability of having more than one bit in error in each transmission is negligible. In Section IV we will see that the expressions derived using Eq. 12 can predict the true performance of the system considerably well.

Averaging over fading, we will have,

$$E(w_c^2(k)) = \Delta^2 \sum_{i=0}^{N_b-1} 2^{2i} \overline{P_{b,N_b-1-i}^k}. \quad (14)$$

For a BPSK modulation we will have [9],

$$P_{b,i}^k = Q(\sqrt{SNR_i^k}), \quad (15)$$

where $SNR_i^k = \frac{|h_i^k|^2 \sigma_b^2}{\sigma_n^2}$ represents the instantaneous Signal to Noise Ratio. σ_b^2 is the transmitted signal power and $\sigma_n^2 = .5 \times \overline{(n^k)^2}$ where n^k is a sample of baseband AWGN, as defined in Eq. 7. Therefore for a Rayleigh distributed $|h_i^k|$, we will have [10]:

$$E(w_c^2(k)) = \Delta^2 \times \frac{4^{N_b}-1}{6} \times (1 - \sqrt{\frac{.5\Gamma}{1+.5\Gamma}}), \quad (16)$$

where $\Gamma = \frac{\sigma_h^2 \sigma_b^2}{\sigma_n^2}$ represents the average received Signal to Noise Ratio with $\sigma_h^2 = \overline{|h_i^k|^2}$ denoting the power of the channel fading coefficient.

Next we calculate $\overline{w_c(k)w_c(k')}$ for $k \neq k'$. We will have,

$$Prob\{w_c(k)w_c(k') = \Delta^2 \times 2^s\} =$$

$$\sum_{i+i'=s} Prob\{w_c(k) = \Delta \times 2^i \ \& \ w_c(k') = \Delta \times 2^{i'}\} +$$

$$\sum_{i+i'=s} Prob\{w_c(k) = -\Delta \times 2^i \ \& \ w_c(k') = -\Delta \times 2^{i'}\}. \quad (17)$$

$Prob\{w_c(k) = \Delta \times 2^i \ \& \ w_c(k') = \Delta \times 2^{i'}\}$ is the probability that $(N_b-1-i)^{th}$ bit in the kth transmission and $(N_b-1-i')^{th}$ bit in the k'^{th} transmission are flipped from zero to one. Therefore, we will have,

$$Prob\{w_c(k) = \Delta \times 2^i \ \& \ w_c(k') = \Delta \times 2^{i'}\} =$$

$$\frac{1}{4} \int_{g_i^k} \int_{g_{i'}'^{k'}} Q(\frac{g_i^k \sigma_b}{\sigma_n}) Q(\frac{g_{i'}'^{k'} \sigma_b}{\sigma_n}) f_{g_i^k, g_{i'}'^{k'}} dg_i^k dg_{i'}'^{k'}, \quad (18)$$

where $g_i^k = |h_{N_b-1-i}^k|$, $g_{i'}'^{k'} = |h_{N_b-1-i'}^{k'}|$ and $f_{g,g'}$ represents the bivariate Rayleigh distribution. Similarly,

$$Prob\{w_c(k)w_c(k') = -\Delta^2 \times 2^s\} =$$

$$\sum_{i+i'=s} Prob\{w_c(k) = -\Delta \times 2^i \ \& \ w_c(k') = \Delta \times 2^{i'}\} +$$

$$\sum_{i+i'=s} Prob\{w_c(k) = \Delta \times 2^i \ \& \ w_c(k') = -\Delta \times 2^{i'}\}. \quad (19)$$

It can be easily shown that for any term in Eq. 17, there exists a corresponding term with the same value in Eq. 19 resulting in the following,

$$Prob\{w_c(k)w_c(k') = \Delta^2 \times 2^s\} =$$
$$Prob\{w_c(k)w_c(k') = -\Delta^2 \times 2^s\} \quad (20)$$

which results in $\overline{w_c(k)w_c(k')} = 0$ for $k \neq k'$ (they are still dependent). Therefore we will have,

$$E(y^2(k)) = \beta^{2k}y^2(0) + \gamma^2\alpha^2 \frac{1-\beta^{2k}}{1-\beta^2} E(w^2(k)), \quad (21)$$

where $E(w^2(k)) = E(w_c^2(k)) + E(w_q^2(k))$ with $E(w_c^2(k))$ defined in Eq. 16 and $E(w_q^2(k)) = \frac{\Delta^2}{12}$ for a uniform quantizer. Asymptotic behavior of the mobile sensor, $lim_{k->\infty} E(y^2(k))$, as well a measure of the history of convergence, $\sum_k E(y^2(k))$, can be easily derived using Eq. 21.

B. Deriving $P_{Thresh}(k)$

Next we derive $P_{Thresh}(k)$. Let $\vec{h}_c^k = [\vec{h}^0 \dots \vec{h}^{k-1}]$. We will have,

$$P_{Thresh}(k) = E_{\vec{h}_c^k}(P_{Thresh}(k)|\vec{h}_c^k)$$

$$P_{Thresh}(k)|\vec{h}_c^k = Q(\frac{Thresh+\beta^k y(0)}{\sigma_z^k |\vec{h}_c^k}) + Q(\frac{Thresh-\beta^k y(0)}{\sigma_z^k |\vec{h}_c^k}), \quad (22)$$

where $(\sigma_z^k)^2$ is the variance of $z(k)$ of Eq. 9. Following the analysis of the previous sub-section, we will have:

$$(\sigma_z^k)^2|\vec{h}_c^k = \gamma^2\alpha^2\sum_{i=1}^k \beta^{2(i-1)}\sigma_{w_{k-i}}^2|\vec{h}_c^k$$

$$\sigma_{w_{k-i}}^2|\vec{h}_c^k = \Delta^2\sum_{s=0}^{N_b-1} 2^{2s}Q(\frac{|h_{N_b-1-s}^{k-i}|\sigma_b}{\sigma_n}) + \frac{\Delta^2}{12}. \quad (23)$$

To obtain $P_{Thresh}(k)$ from Eq. 22 and 23, an averaging over the distribution of $\vec{a}_{h_c}^k$ is needed where each element of $\vec{a}_{h_c}^k$ represents the amplitude of the corresponding term in $\vec{h}_c^k$. $\vec{a}_{h_c}^k$ consists of correlated Rayleigh distributed random variables. In case of an exponentially decaying correlation function, $\vec{a}_{h_c}^k$ will have the following pdf [11]:

$$f_{\vec{a}_{h_c}^k}(\vec{u}) = \frac{\prod_{i=1}^{kN_b}\vec{u}_i}{\sigma_h^{2kN_b}(1-\rho^2)^{kN_b-1}} \times$$

$$exp(-\frac{\vec{u}_1^2+\vec{u}_{kN_b}^2+(1+\rho^2)\sum_{i=2}^{kN_b-1}\vec{u}_i^2}{2(1-\rho^2)\sigma_h^2}), \quad (24)$$

where ρ is the correlation coefficient[3] [11]. Using Eq. 24, $P_{Thresh}(k)$ can be calculated as follows:

$$P_{Thresh}(k) = \int_{\vec{a}_{h_c}^k}(P_{Thresh}(k)|\vec{a}_{h_c}^k)f_{\vec{a}_{h_c}^k}d\vec{a}_{h_c}^k. \quad (25)$$

IV. PERFORMANCE OF A WIRELESS SPEED CONTROL SYSTEM

In this section we implement the analysis results of the previous section. We also run exhaustive simulations to confirm the analysis. As an example we consider a wireless speed control problem in which a sensor and an actuator are placed on a mobile unit whose speed is being controlled wirelessly by a controller

---

[3]Depending on the application, ρ may be a function of k.

---

node. Then x represents the speed of the mobile node, $\phi = e^{-\frac{bT}{m}}$ and $\gamma = -\frac{1}{b}(\phi - 1)$ where b and m denote surface friction coefficient and mass of the mobile sensor respectively. At each sampling instant, the mobile unit senses the speed and sends it wirelessly to the controller node. The actuator on the mobile node then adapts the amount of applied force based on the command received from the controller. Starting from an initial speed of $x(0)$, the goal is to stop the mobile node. The fact that the parameter to control is the speed makes the problem particularly interesting as changes in speed directly affects the correlation of the fading coefficient emphasizing the impact of control on communication. The following parameters are chosen for this example: $m = .1$kg, $b = 100$Ns/m, $T = .01$sec, $\alpha = 10$ and the initial speed of $x(0) = 20$m/s. In the ideal case of perfect communication, the speed, x_{ideal}, would asymptotically converge to zero. In fact for the given parameters, after 10 iterations (.1 sec) we will have $x_{ideal}^2(.1\text{sec})=3.9642\text{e-}016$, at which point the control process can be stopped. We choose this amount of time, $t_{test} = .1$sec, to evaluate the performance in the presence of imperfect communication. A 20bit uniform quantizer is used with the range of $[-30\text{m/s},30\text{m/s}]$. Fig. 2 and 3 show the control performance in the presence of imperfect communication. Fig. 2 shows $E(y^2)$ at

t_{test} and as a function of average received SNR. To investigate the contribution of fading, Fig. 2 shows the performance in the absence of fading (but in the presence of AWGN and quantization) as well. We can see that in the presence of fading $E(y^2)$ gets significantly higher values indicating considerable impact of fading on the performance. The "no fading" case has an error floor at high SNR due to the quantization effect. Fig. 2 also shows the performance evaluated using the analytical results of the previous section (the star and circle lines). We can see that the analysis and simulation results match very well except for considerably high SNR scenarios. This is as expected as in the analysis we ignored the correlation of the quantization noise. Since the communication noise gets considerably small values at very high SNR, the impact of quantization noise correlation can not be neglected any more.

To better see the dynamics of the output, Fig. 3 shows P_{Thresh} as a function of $Threshold$ for both cases of "fading" and "no fading". Compared to the "no fading" case, we can see that with higher probabilities the mobile node will have significantly higher speeds in the presence of fading. As SNR increases, fading degrades the performance more considerably. At very high SNR we can see that the "no fading" case reaches

an error floor as explained for[4] Fig. 2. Fig. 2 and 3 showed that, depending on the system requirements, fading can result in a considerable delay and/or poor performance of the mobile sensor. Therefore its impact on the control process can not be neglected.

V. ADAPTATION IN APPLICATION LAYER

As we saw in the previous section, fading can degrade the performance of the control system considerably depending on the dynamics of the mobile node and the communication channel. This suggests that we may benefit from passing the knowledge of the communication channel to the application layer. In other words, the controller should adapt the control commands to the quality of the communication link adding a trust coefficient to its estimate of the sensor measurement. If the channel status is good (i.e. $|h|$ is large), then the controller should choose large α. On the other hand, when the channel is in deep fade (i.e. $|h|$ is small), the controller estimate of the sensor measurement should not be trusted and α should be chosen small. This suggests adapting the α of Eq. 3 to

[4]Fig. 3 is obtained from simulation results. It is possible to calculate Eq. 25 for smaller values of t_{test}. However, calculating it for large t_{test} is challenging for this particular problem due to the fact that ρ of Eq. 24 changes drastically in the time duration t_{test} as speed changes. We are currently working on approximating ρ in order to utilize Eq. 25 for these types of problems.

the communication link quality. Then we will have,

$$u(k) = -\alpha_{adapt}(k) \times \hat{y}(k) \quad where$$

$$\alpha_{adapt}(k) = \alpha_{fixed} \times G(\vec{h}^k) \quad where$$

$$G_1(\vec{h}^k) = \frac{\sum_{m=0}^{N_b-1} |h_m^k|}{N_b \sigma_h} \qquad (26)$$

$$G_2(\vec{h}^k) = \frac{h_0^k}{\sigma_h},$$

where $G(\vec{h}^k)$ is a function of the channel at k^{th} transmission. As the channel may change during a transmission, G can be defined in different ways. Eq. 26 shows two possibilities (G_1 and G_2). G_1 uses sum of the absolute values of the channel during each transmission and G_2 uses the value of the channel at the most significant bit. Since with high probability changes of the channel during each transmission are minor, both functions would yield similar results with high probability. α_{fixed} denotes the case of fixed α of the previous sections. σ_h^2 is the power of the fading coefficient and is added so that $E(\alpha_{adapt}^2(k)) = \alpha_{fixed}^2$ to facilitate comparison with the no adaptation case. Fig. 4 and 5 show the performance when application layer is adapting to the quality of the physical layer. When adapting, using either G_1 or G_2 results in the same curves for this example. Comparing with the no adaptation case, we can see a considerable improvement in the performance. Fig. 4 shows that $E(y^2)$ gets considerably smaller values after adaptation. Fig. 5 shows a shift of $P_{Threshold}$ curves towards smaller values. The results emphasize the importance of sharing information between communication and control layers.

VI. PRACTICAL ISSUES

In this paper the effect of fading was studied for the case that channel is perfectly estimated in the receiver. Even for such a scenario, we saw that fading degrades the performance considerably. Adding the impact of imperfect channel estimation will further degrade the control performance.

Similarly we used perfect knowledge of the channel at the receiver when adapting. In practice an estimate of the channel should be used. Furthermore, if the channel is changing too fast that obtaining an estimate of the channel in each transmission is not possible, then we can adapt to the statistics of the channel which are changing slower.

VII. SUMMARY

In this paper we studied the impact of time-varying communication links on the control performance of a mobile sensor node. We derived key performance measure parameters to evaluate the overall feedback control performance over narrowband channels. We showed that fading can result in a considerable delay and/or poor performance of the mobile sensor. Then we showed that application layer can use the channel

status information of the physical layer to adapt control commands accordingly. We showed that sharing information across layers can improve the overall performance considerably. The analytical results were verified by simulating a wireless speed control problem.

VIII. NEXT STEP

We are currently working on optimizing the adaptation by understanding the amount of sufficient information that application layer needs to know about the physical layer to meet system requirements. Furthermore, we are working on extending the work presented in this paper to a cooperative and decentralized mobile sensor/actuator network. Then the decisions are made at each mobile node based on the local sensor measurements and the received measurements from other nodes. Therefore, the quality of the communication links would affect the overall performance and should be considered.

REFERENCES

[1] C. Chong and S. Kumar, 'Sensor networks: evolution, opportunities and challenges," Proceedings of the IEEE, vol. 91, issue 8, Aug. 2003, pages:1247-1256

[2] B. Sinopoli, C. Sharp, L. Schenato, S. Schaffert and S. Sastry, 'Distributed control applications within sensor networks," Proceedings of the IEEE, vol. 91, issue 8, Aug. 2003, Pages:1235-1246

[3] L. Xiao, M. Johansson, H. Hindi, S. Boyd and A. Goldsmith, 'Joint optimization of communication rates and linear systems," IEEE trans. on automatic control, vol. 48, no. 1, Jan. 2003

[4] X. Liu and A. Goldsmith, 'Wireless communication tradeoffs in distributed control," 42nd IEEE Conference on Decision and Control, volume: 1, 2003, pages:688 - 694

[5] X. Liu and A. J. Goldsmith, 'Wireless medium access control in distributed control systems," Allerton Conference on Communication, Control and Computing, 2003

[6] S. Tatikonda, A. Sahai and S. Mitter, 'Control of LQG systems under communication constraints," IEEE 37th Conference on Decision and Control, 1998, vol. 1, Pages:1165-1170

[7] R. Wang and D. Cox, 'Double mobility mitigates fading in ad hoc wireless networks." IEEE Antennas and Propagation Society Symp., 2002

[8] Carlson, Crilly and Rutledge, *Communication Systems*. 4th edition

[9] Proakis, *Digital Communications*. MacGraw-Hill, 1995

[10] William Jakes, *Microwave Mobile Communications*. IEEE Press, 1974

[11] R. Mallik, 'On multivariate Rayleigh and exponential distributions," IEEE Trans. on Info. Thoery, vol. 49, no. 6, June 2003
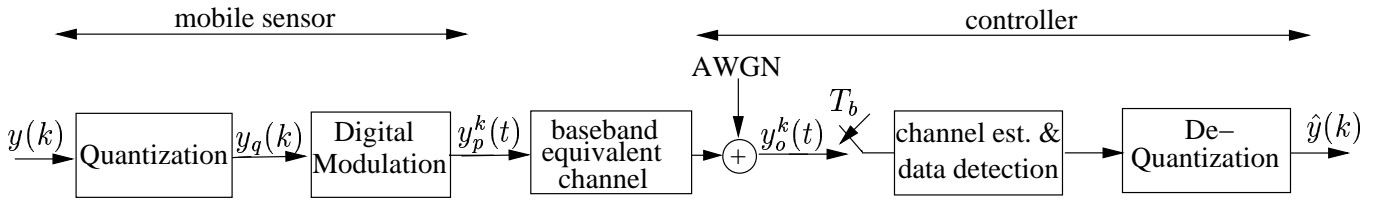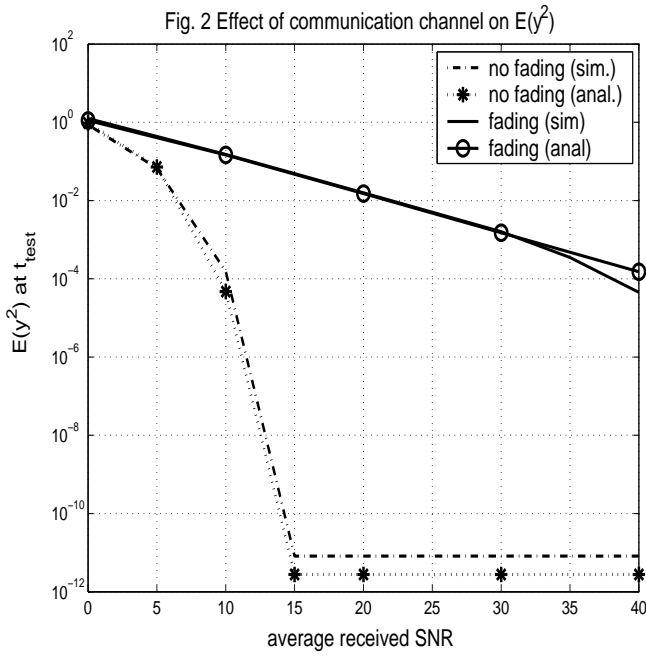
Fig. 1 Transmission over wireless channel
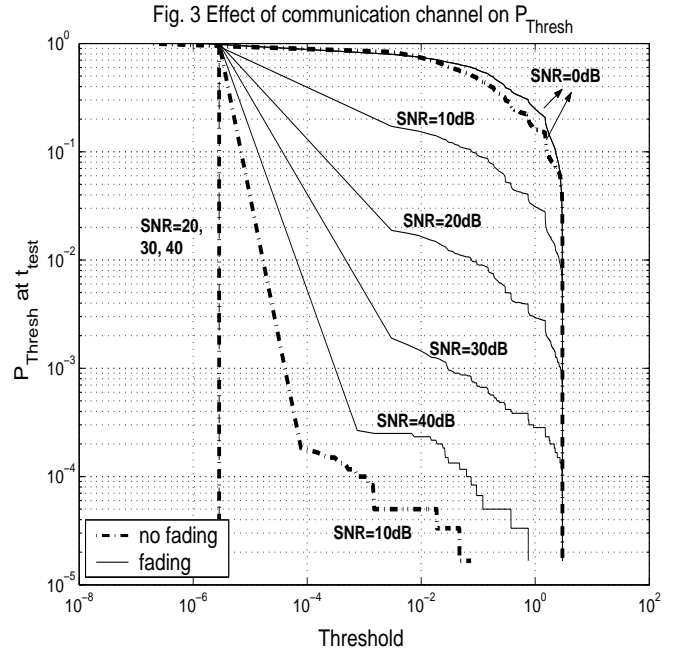

Fig. 2 Effect of communication channel on $E(y^2)$

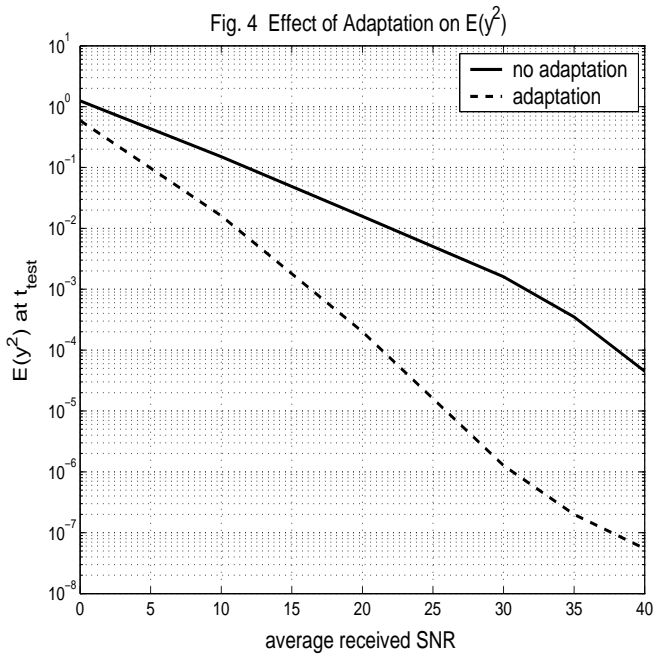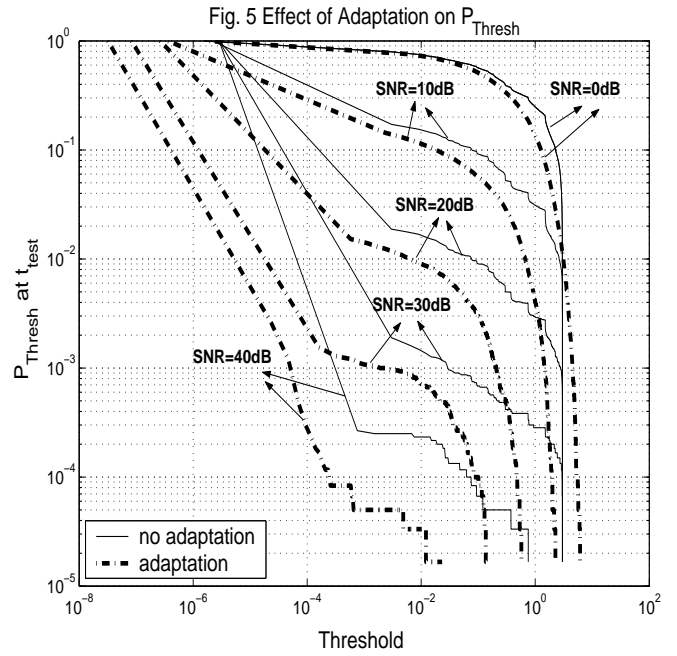Fig. 3 Effect of communication channel on P_{Thresh}

Fig. 4 Effect of Adaptation on $E(y^2)$

Fig. 5 Effect of Adaptation on P_{Thresh}