Minimization of Transceiver Energy Consumption in Wireless Sensor Networks

Presented by

Tianqi Wang

2008-7-15

Outline

- **Introduction**
  - **System model**
  - **Packet structure**
  - **Retransmission mechanism**
- **The model of energy consumption per information bit**
- **Numerical results**
  - **Unconstrained**
  - **Constrained**
- **Conclusions**
- **Current researches**

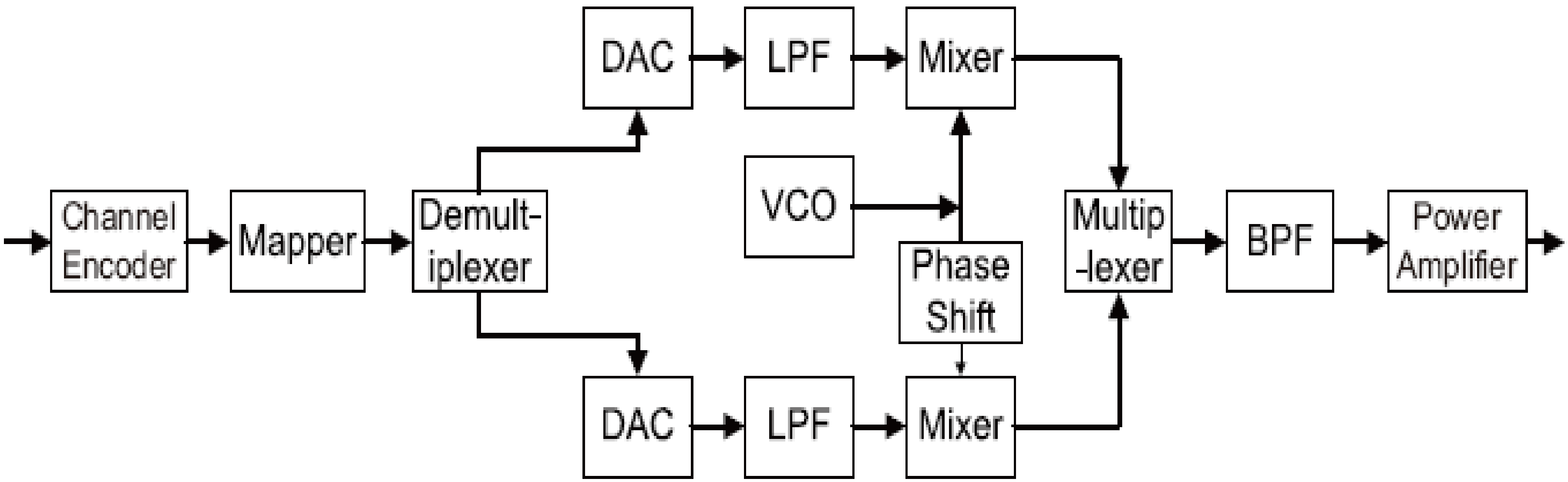
Introduction

- **Motivation**:
  - Minimizing Energy Consumption is a very importance design consideration when frequent battery replacement is impractical (such as in wireless sensor networks (WSN))
  - Given the difficulties of joint optimization of all layers, a pair-wise PHY-layer optimization is considered.
  - In short-distance wireless communication systems (such as densely distributed WSN), **circuit energy consumption** and **transmission energy consumption** should both be considered.

Introduction

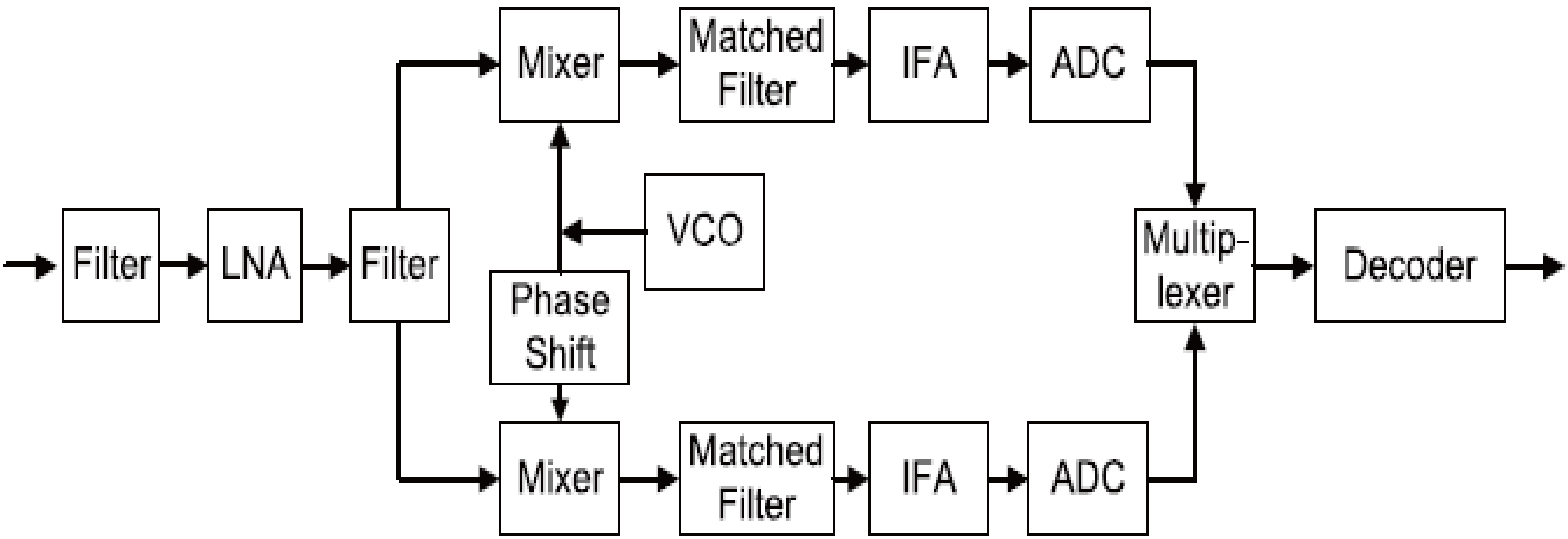
- **Target**
  - Minimize energy consumption per information bit considering the impacts of overhead and retransmission;
- **Adjustable Parameters**
  - **Packet length**
    - Tradeoff between overhead and retransmission probability;
  - **Target bit error probability**
    - Tradeoff between transmission power consumption and retransmission probability;
  - **Modulation**
    - Tradeoff between bandwidth efficiency and energy efficiency;
  - **Bandwidth**
    - Tradeoff between transmission time duration and frequency-selective fading

System model



- Fig. A typical transmitter architecture

System model



- Fig. A typical receiver architecture

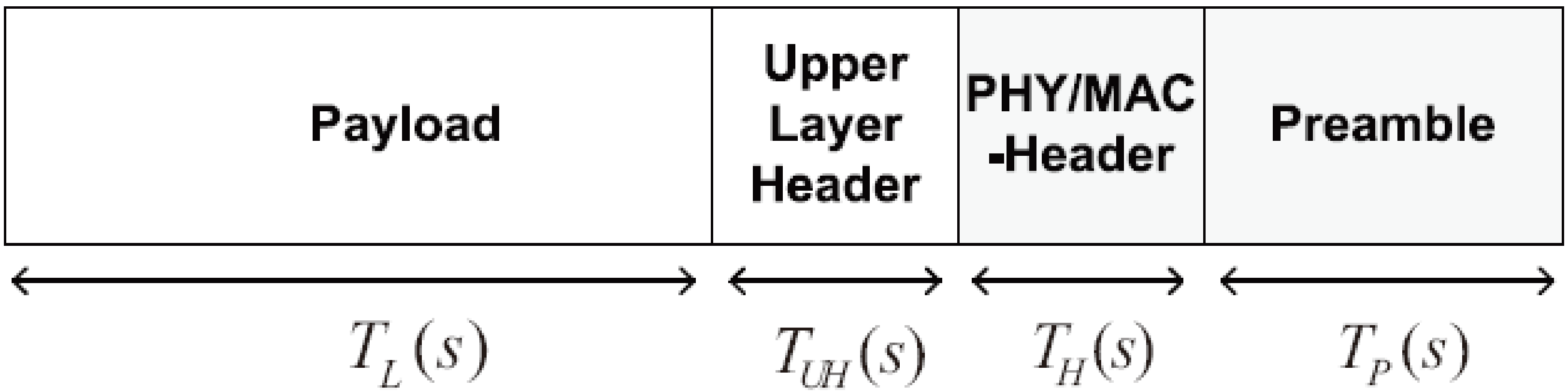
System model

- Total energy required to transmit/receive one packet

$$
\begin{aligned}
E &= P_{on}T_{on} \\
&= (P_t + P_{amp} + P_c)T_{on} \\
&= (P_t + \beta P_t + P_c)T_{on}
\end{aligned}
$$

  - The energy consumption when the transceiver is in active mode (modulation/demodulation, filter, power amplifier, ADC/DAC, mixer, frequency synthesizer)

Packet structure



- Fig. Packet Structure

Retransmission mechanism

- **A packet will be retransmitted whenever this packet is viewed as in error.**

$$P_{pc} = \sum_{n_e=0}^{N_{max}} \binom{L_L + L_{UH}}{n_e} P_b^{n_e} (1 - P_b)^{L_L + L_{UH} - n_e}$$

Energy Consumption per Information Bit

- **The energy consumption of transmitting/receiving one packet**

$$\gamma = \frac{P_r}{P_{noise}}$$

$$P_{noise} = 2BN_0$$

$$P_r = P_t / G(d)$$

$$E = (1+\beta)2BN_0 G(d) f(P_b) T_{on}/G_c + P_c T_{on}$$

$$T_{on} = (T_L + T_{UH} + T_H)/R_c + T_p$$

Energy Consumption per Information Bit

- **Bit Error Probability w.r.t. SNR per Symbol**

Modulation	$P_b(\gamma)$	η (bits/Hertz)
BPSK	$P_b = Q(\sqrt{2\gamma}) \leq \frac{1}{2}e^{-\gamma}$	$\eta = 1$
MPSK	$P_b = \frac{2}{log_2 M} Q(\sqrt{2\gamma}\sin(\frac{\pi}{M})) \leq \frac{1}{log_2 M} e^{-\gamma \sin^2(\frac{\pi}{M})}$	$\eta = log_2 M$
MQAM	$P_b \approx \frac{4}{log_2 M} Q(\sqrt{\frac{3\gamma}{M-1}}) \leq \frac{2}{log_2 M} e^{-\frac{3}{2(M-1)}\gamma}$	$\eta = log_2 M$
MFSK	$P_b \approx \frac{M-1}{log_2 M} Q(\sqrt{\gamma}) \leq \frac{M-1}{2log_2 M} e^{-\frac{\gamma}{2}}$	$\eta = \frac{2log_2 M}{M}$

Energy Consumption per Information Bit

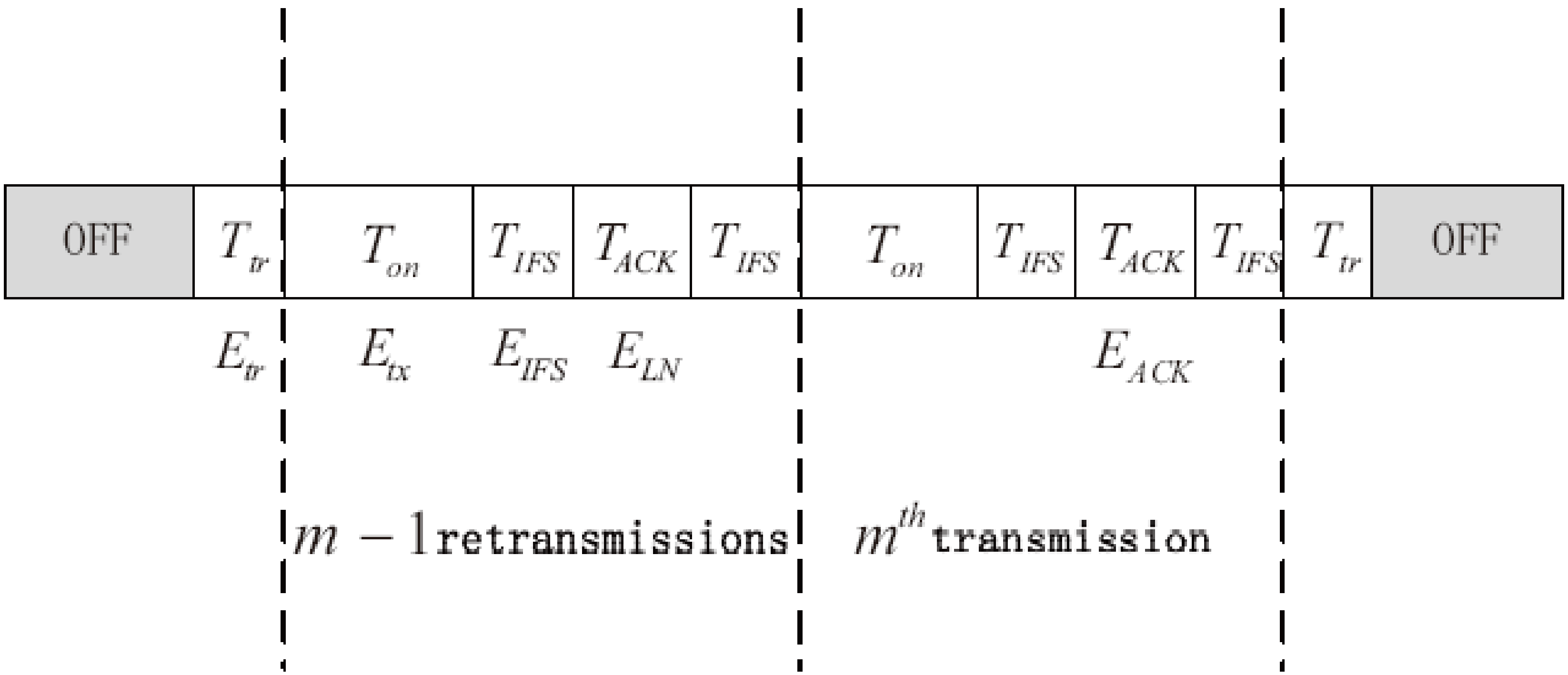


Fig. transmit one packet with m transmissions

Energy Consumption per Information Bit

- **The Energy Consumption during Each Time Period**

$$\begin{aligned} E_{tr} &= P_{syn}T_{tr}, \\ E_{IFS} &= P_{syn}T_{IFS}, \\ E_{LN} &= (P_{cr} - P_v)T_{ACK}, \\ E_{ACK} &= P_{cr}T_{ACK}, \\ E_{tx} &= [(1+\beta)2BN_0G(d)f(P_b)/G_c + P_{ct}]T_{on}. \end{aligned}$$

- **The Transmit Energy Consumption of m transmissions**

$$\begin{aligned} E_t(m) &= (2E_{IFS} + E_{tx} + E_{LN})(m-1) + 2E_{tr} \\ &+ 2E_{IFS} + E_{tx} + E_{ACK}. \end{aligned}$$

Energy Consumption per Information Bit

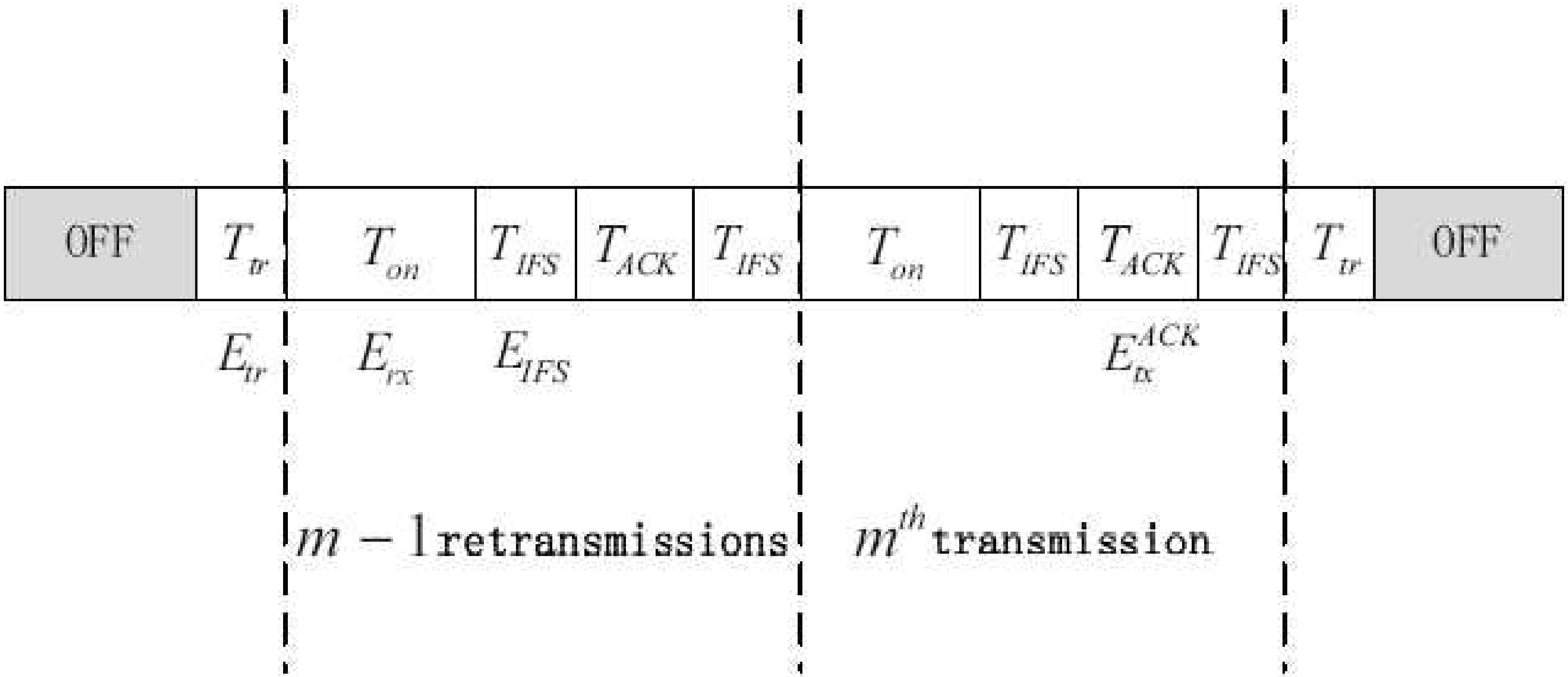


Fig. receive one packet with m transmissions

Energy Consumption per Information Bit

- **The Energy Consumption during Each Time Period**

$$\begin{aligned} E_{tr} &= P_{syn} T_{tr}, \\ E_{IFS} &= P_{syn} T_{IFS}, \\ E_{tx}^{ACK} &= P_t^{'} T_{ACK}, \\ E_{rx} &= P_{cr} T_{on}. \end{aligned}$$

- **The Receiving Energy Consumption of m transmissions**

$$E_r(m) \quad = (2E_{IFS} + E_{rx})m + 2E_{tr} + E_{tx}^{ACK}$$

Energy Consumption per Information Bit

- **The Average Energy Consumption**

$$\bar{E}_t = \sum_{i=1}^{\infty} E_t(i)\Pr\{m = i\}$$

$$\bar{E}_r = \sum_{i=1}^{\infty} E_r(i)\Pr\{m = i\}$$

- **Packet Error Probability**

$$P_{pe} = 1 - (1 - P_b)^L$$

- **The Probability of Transmission Number = m,**

$$P_r(m = i) = P_{pe}^{\,i-1}(1 - P_{pe})$$

Energy Consumption per Information Bit

- **The Average Energy Consumption to Transmit/receive K information bits**

$$\bar{E}_{total} = \frac{K}{L_L}(\bar{E}_r + \bar{E}_t)$$

$$\bar{E}_t \approx \frac{(2E_{IFS} + E_{tx} + E_{LN})}{1 - P_{pe}} + 2E_{tr} + P_v T_{ACK}$$

$$\bar{E}_r \approx \frac{(2E_{IFS} + E_{rx})}{1 - P_{pe}} + 2E_{tr} + E_{tx}^{ACK}$$

Energy Consumption per Information Bit

- **To minimize the energy consumption of transmitting/receiving one information bit (consider retransmission and overhead)**

$$\frac{\partial \bar{E}_{bit}(B, d, L_L, P_b)}{\partial P_b} = 0$$

$$\frac{\partial \bar{E}_{bit}(B, d, L_L, P_b)}{\partial L_L} = 0$$

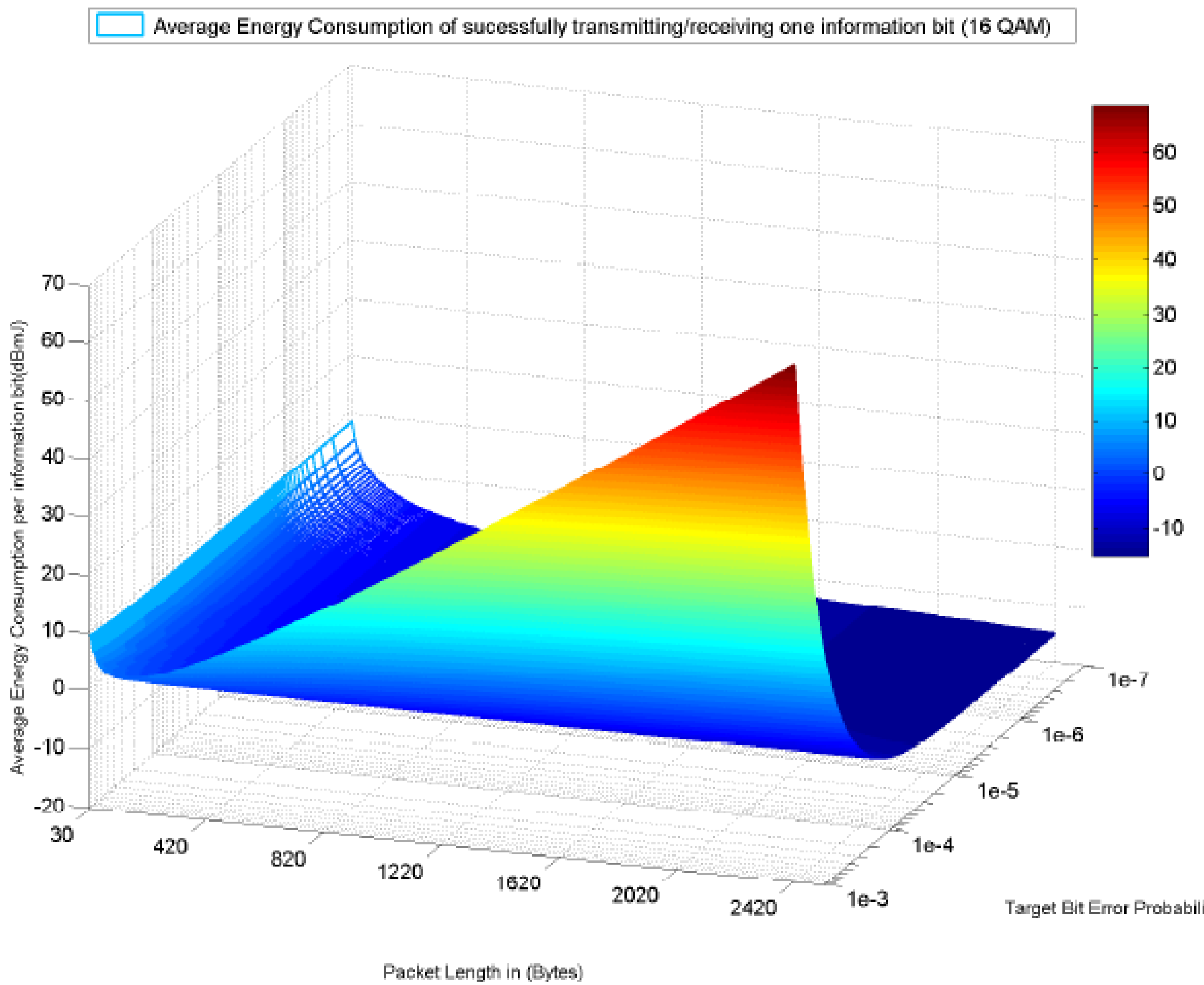
Energy Consumption per Information Bit

- **To minimize the energy consumption of transmitting/receiving one information bit (consider retransmission and overhead)**

$$L_L^* = \frac{-B_1 + \sqrt{B_1^2 - 4A_1C_1}}{2A_1}$$

$$P_b^* \approx \frac{1}{1+(L_L+L_{UH})[\ln(\frac{2}{b})+10+\frac{P_cT_{on}+4E_{IFS}+E_{LN}}{\frac{2}{3}(2^b-1)A_2}]}$$

Numerical Results



Unconstrained

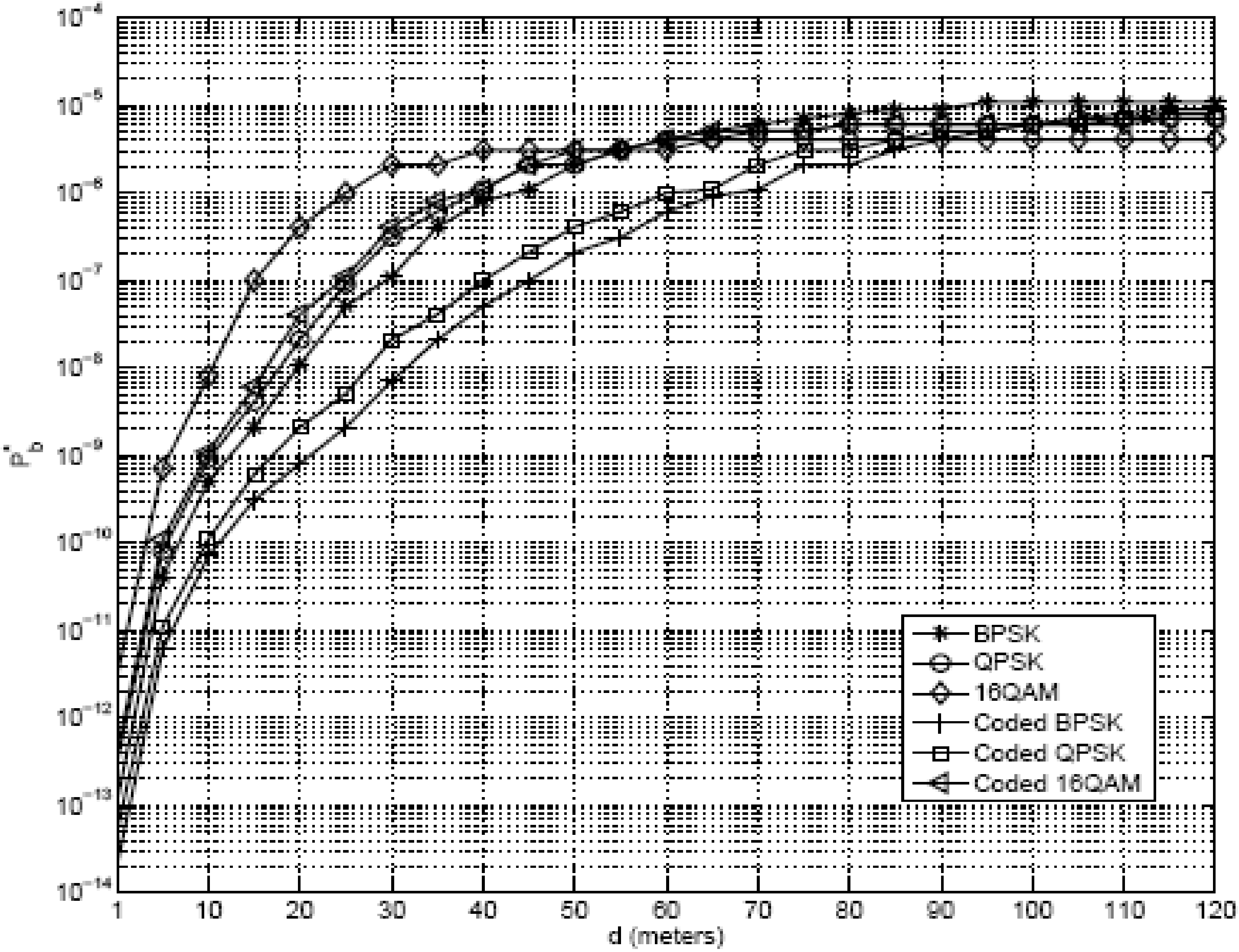


Fig. The optimum target bit error probability v.s. distance

Unconstrained

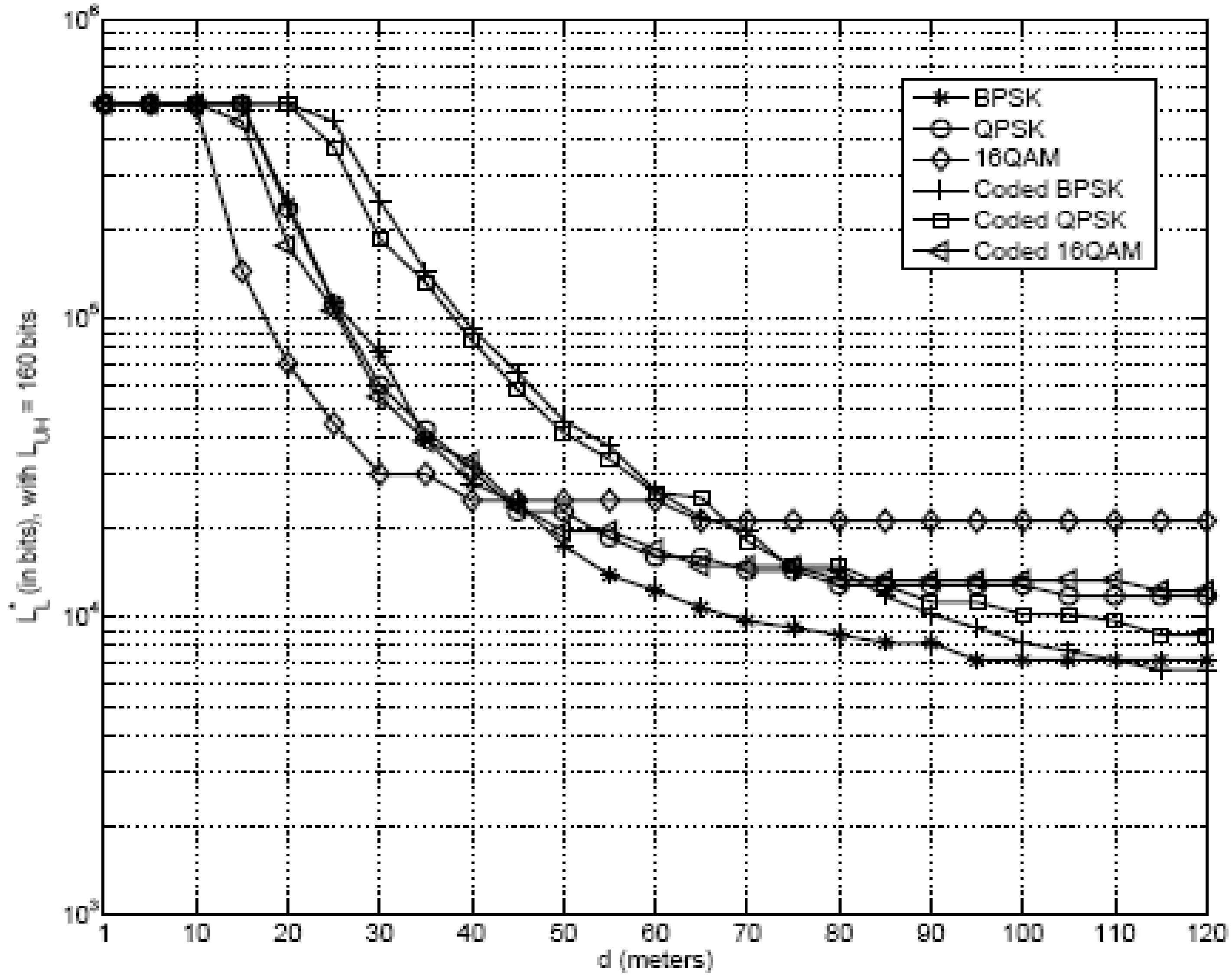


Fig. The optimum packet length v.s. distance

Unconstrained

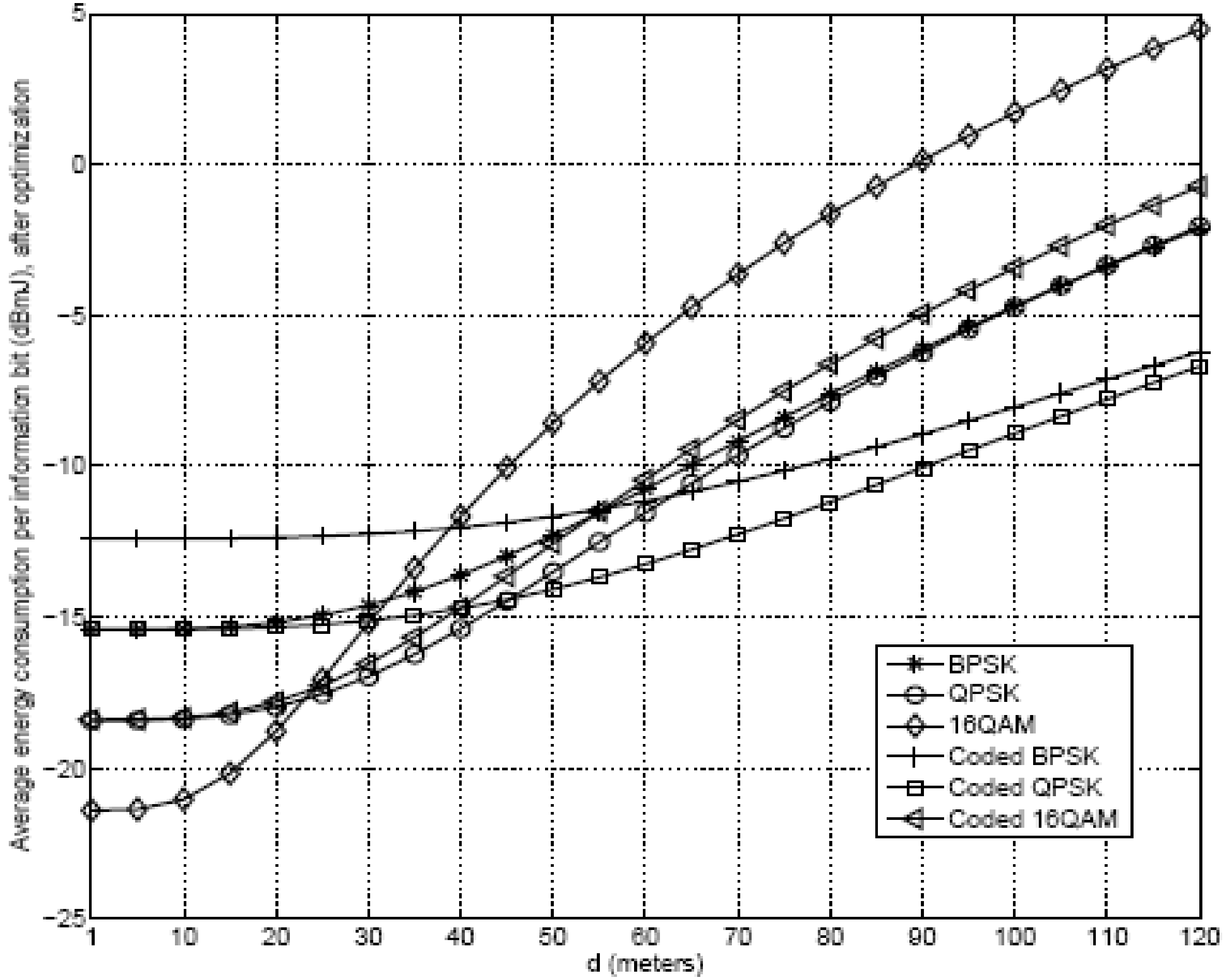


Fig. The optimized energy consumption v.s. distance

Unconstrained

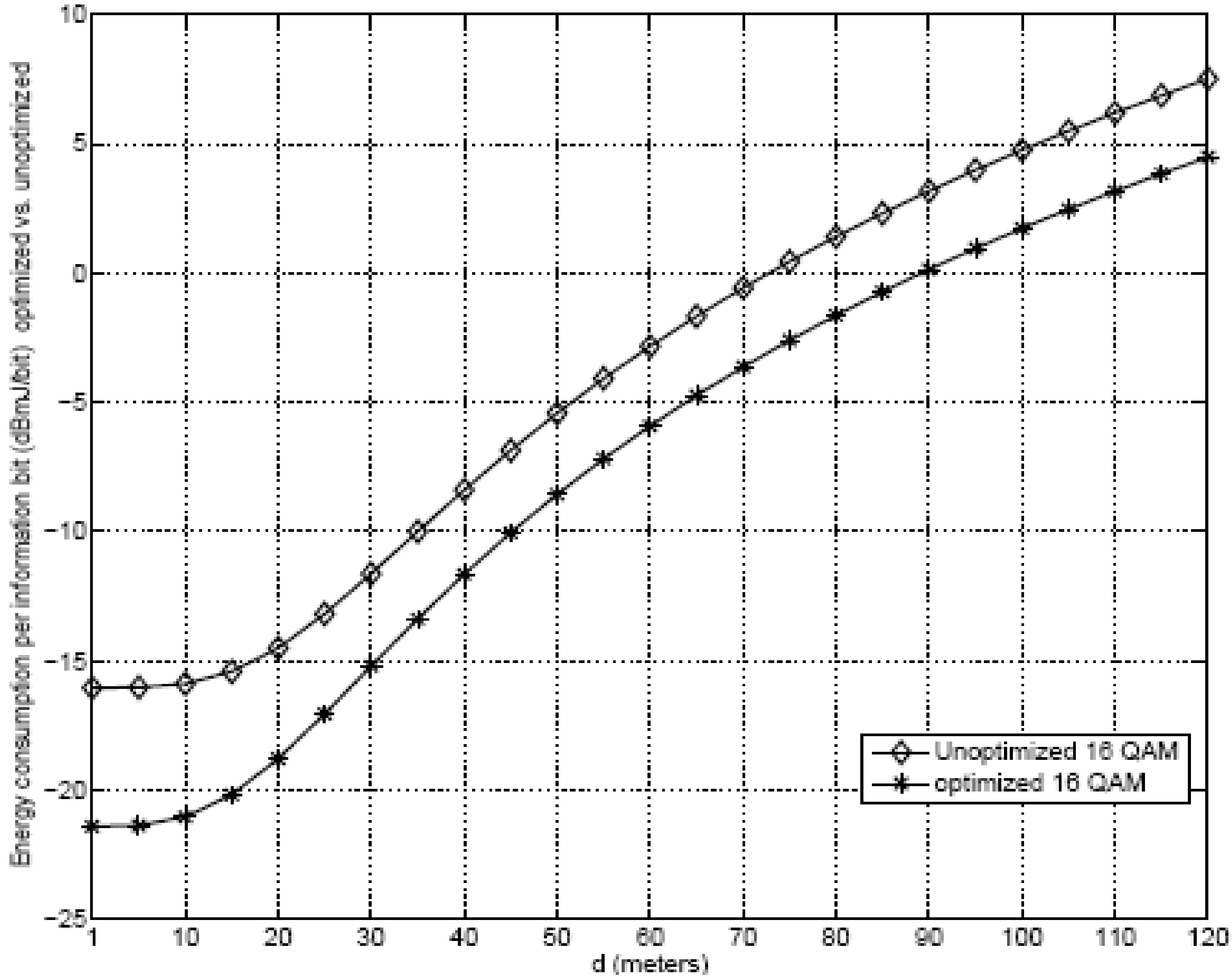


Fig. The optimization gain v.s. distance

Unconstrained

- The Configuration as reference is $P_b = 10^{-4}$ $L_L = 128$ Bytes

OPTIMIZATION GAIN COMPARED TO A CASE WITH FIXED VALUES $P_b = 10^{-4}$ AND $L_L = 127$ BYTES

Modulation and coding	Gain ($d = 120m$)	Gain ($d = 5m$)
BPSK	0.95dB	2.64 dB
Coded BPSK	0.76dB	2.05 dB
QPSK	1.77dB	3.75 dB
Coded QPSK	1.20dB	2.80 dB
16QAM	3.03dB	5.36 dB
Coded 16QAM	1.94dB	3.99 dB

Fig. The Optimization Gain

Constrained

$$
\begin{aligned}
\min \quad & f(b, P_b, L_L) \\
\text{subject to} \quad & \\
& P_{tx}(n_i) \leq P_{max}; \\
& N \leq N_{max}; \\
& \bar{E}_{bit}(n_i) \leq \bar{E}_{bit,max}(n_i); \\
& P_t(n_i) \geq 0; P_r(n_i) \geq 0; \\
& 0.5 \geq P_b \geq 0; L_{max} \geq L_L \geq 0; \\
& b \in \{1, 2, 3, 4, 5, 6, 7, 8\}.
\end{aligned}
$$

Constrained

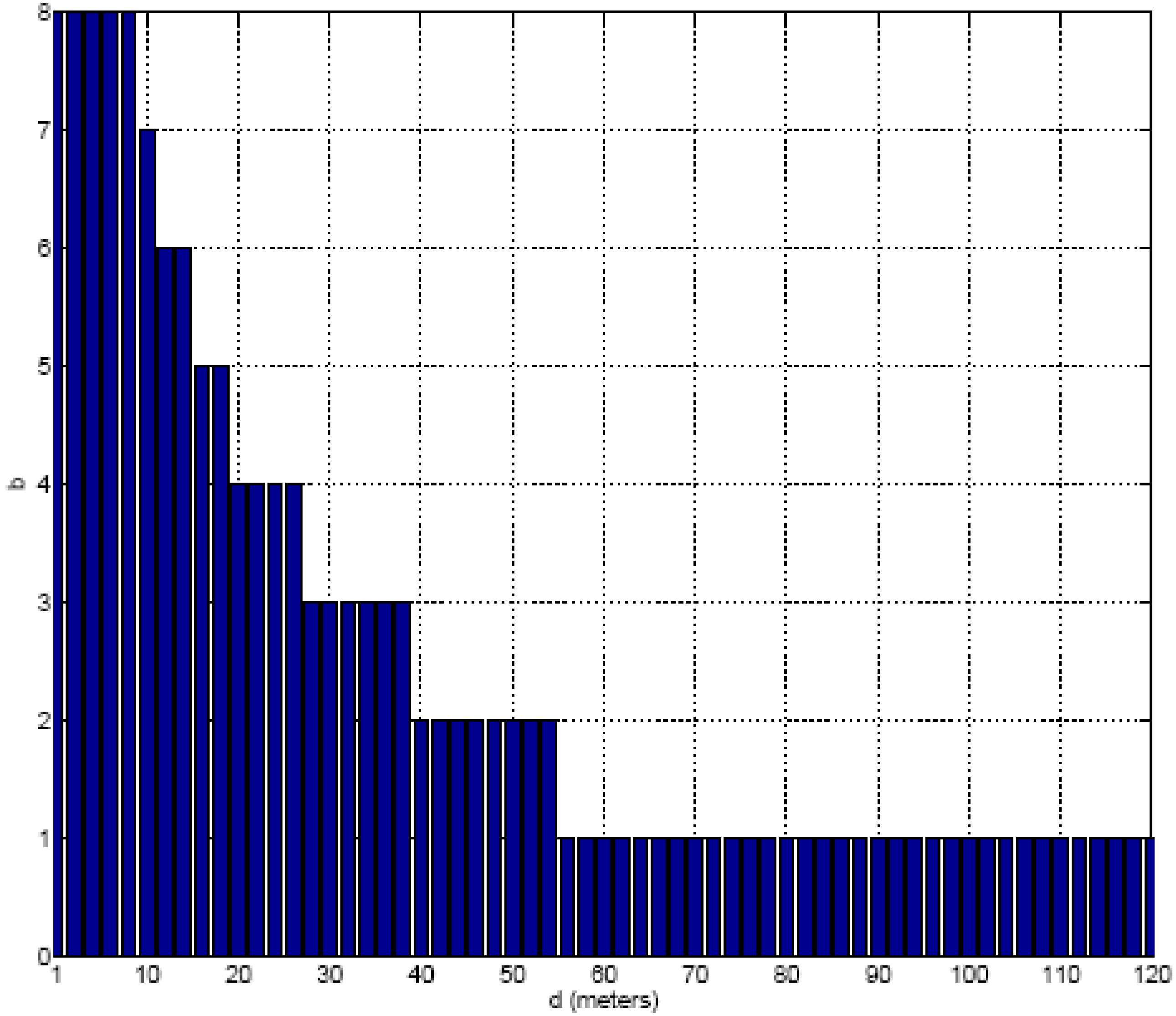


Fig. The optimum constellation size v.s. distance

Constrained

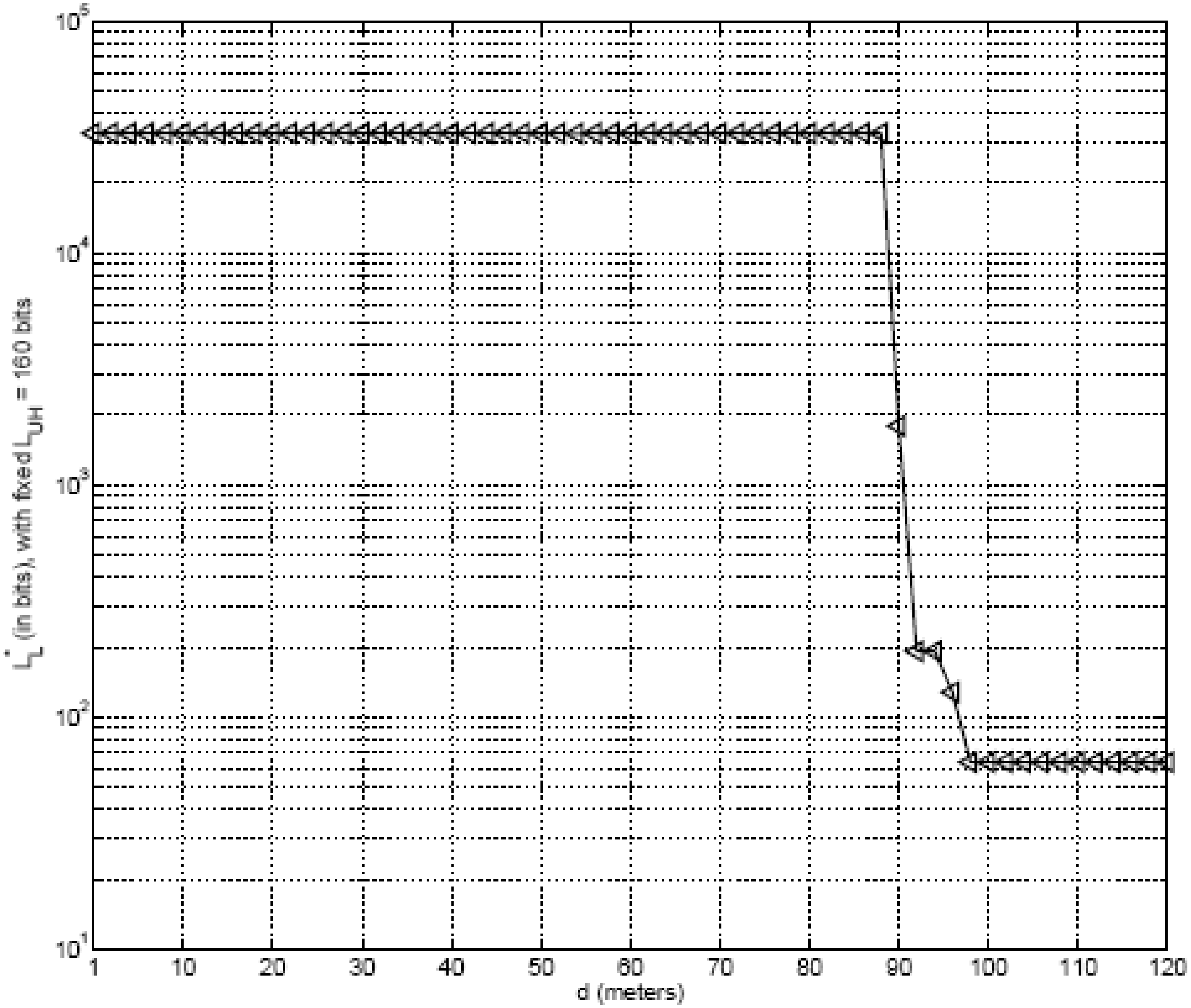


Fig. The optimum packet length v.s. distance

Constrained

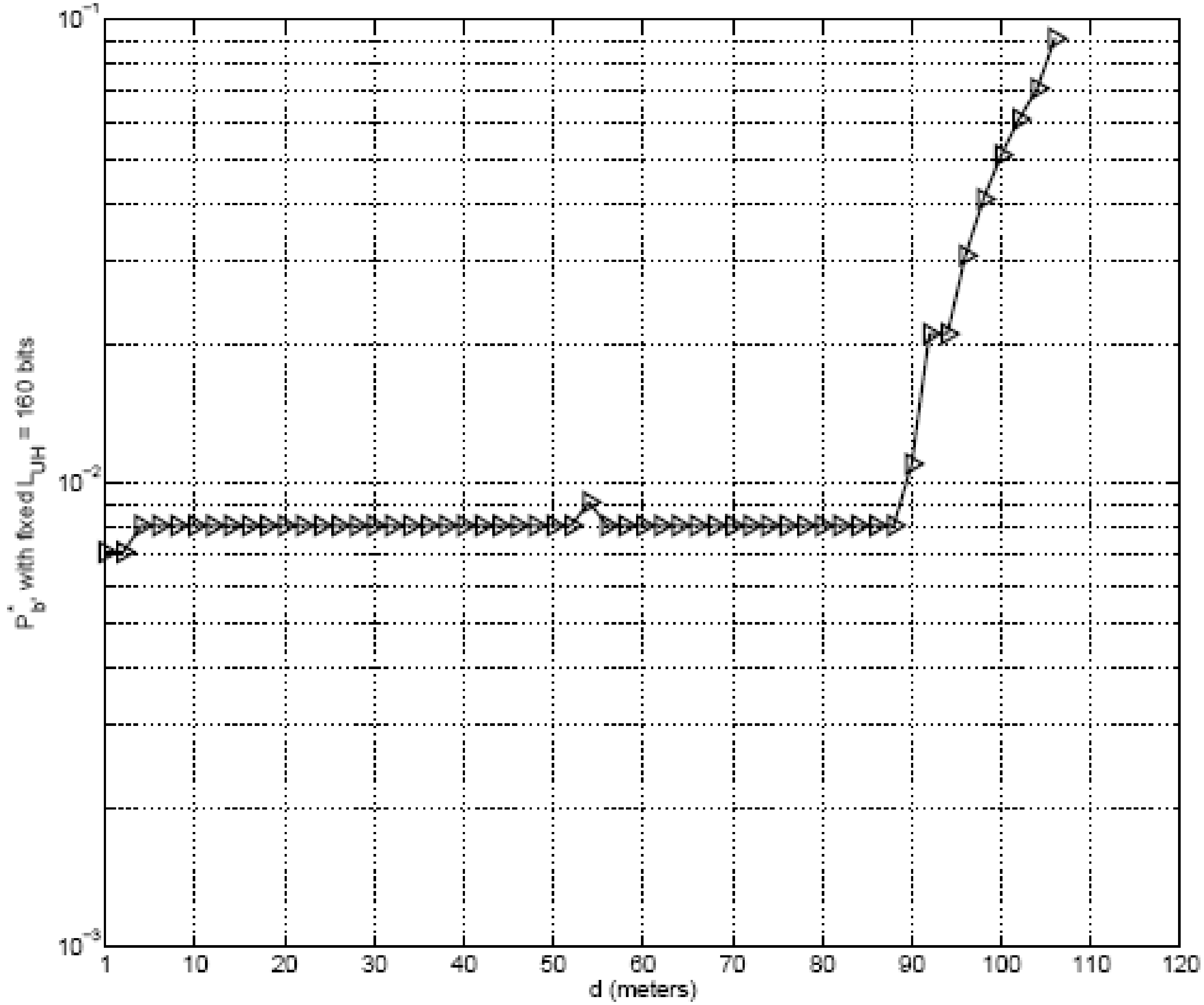


Fig. The optimum target bit error probability v.s. distance

Constrained

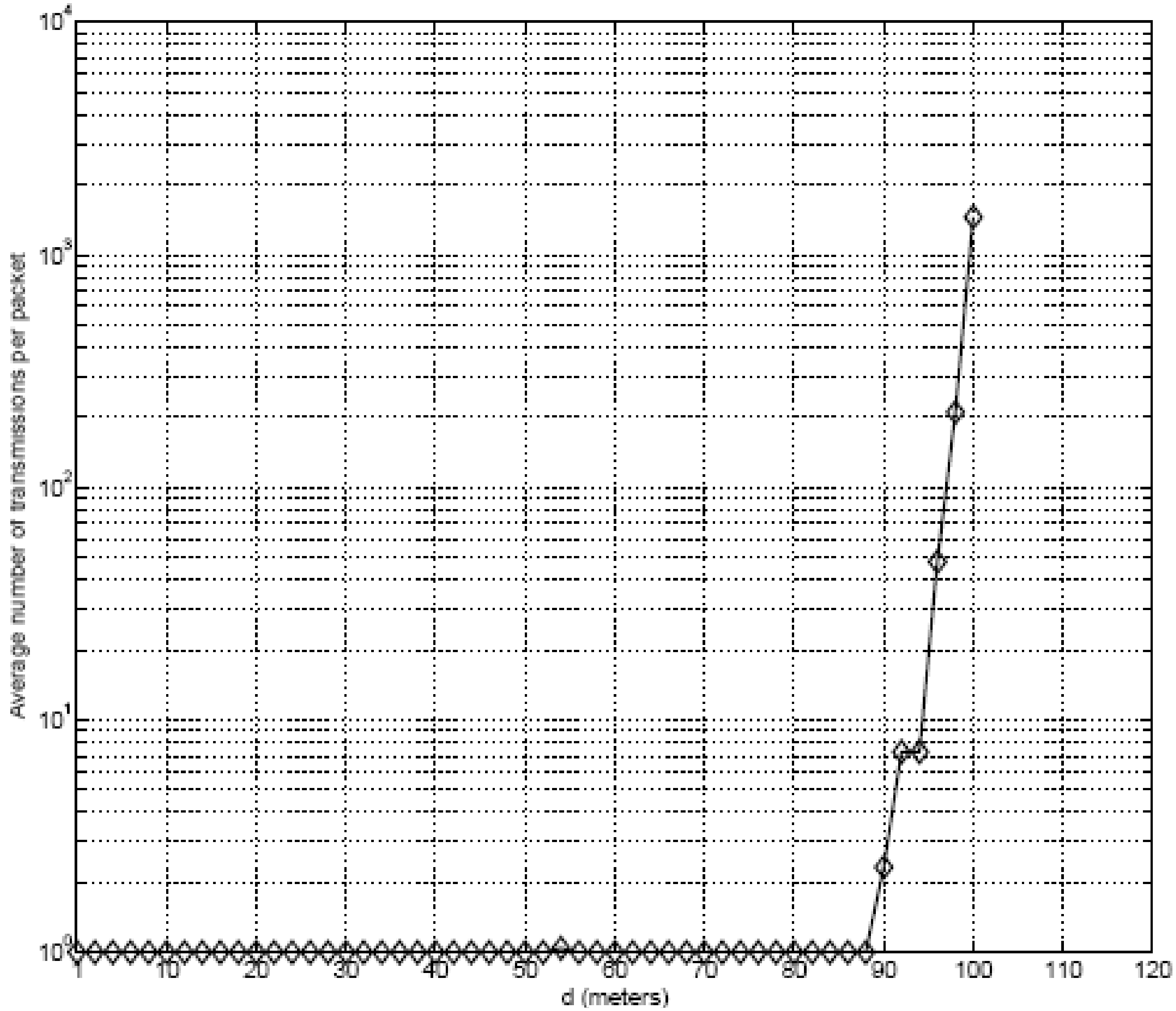


Fig. The optimum retransmission number v.s. distance

Constrained

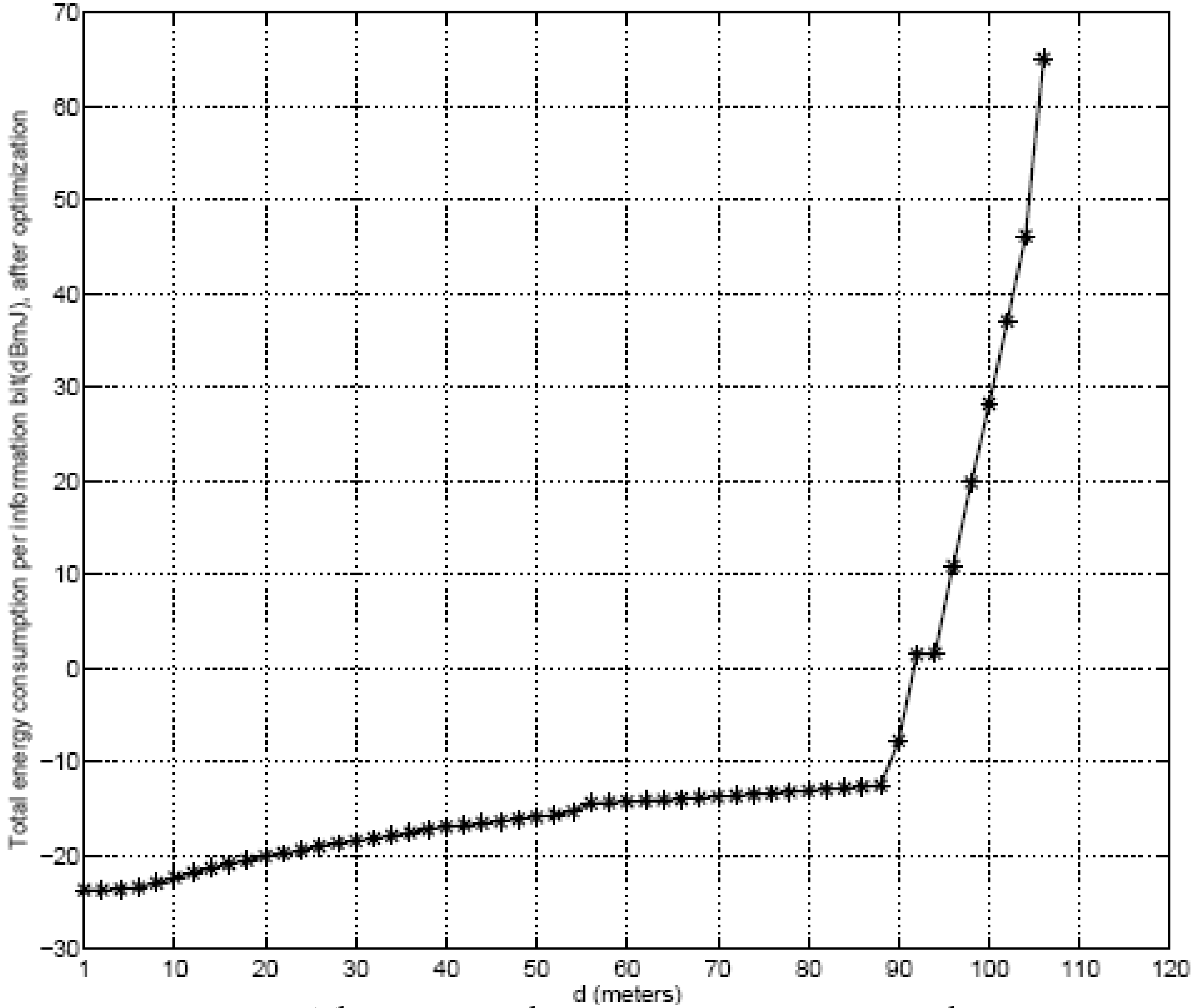


Fig. The optimized energy consumption v.s. distance

Constrained

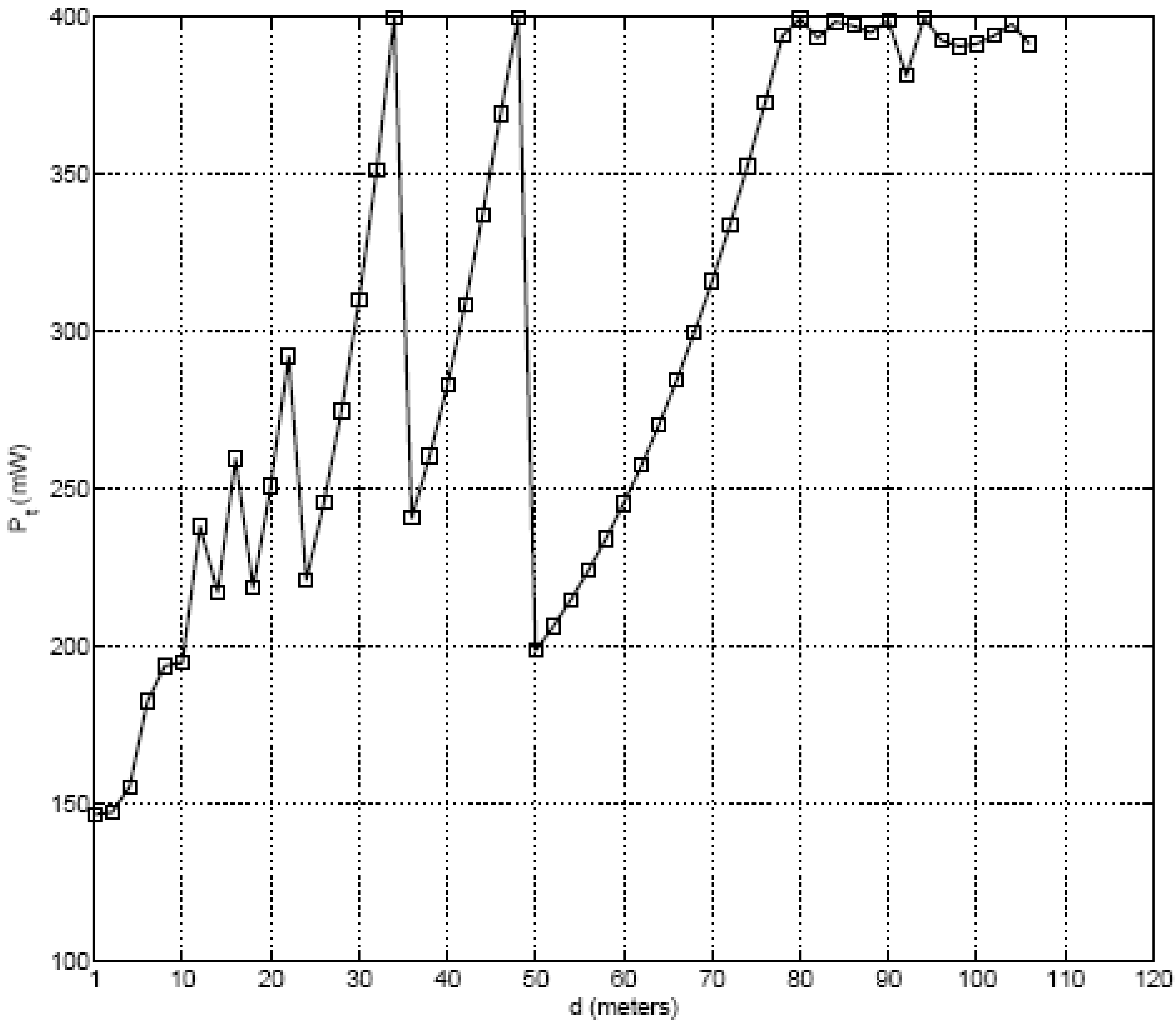


Fig. The optimized power consumption v.s. distance

Conclusions

- An optimization over **target bit error probability** and **packet length** is proposed to minimize the energy consumption per information bit with the consideration of retransmission;
- **Uncoded** modulation with **large** constellation size is energy efficient at **short** transmission distance, while **coded** modulation with **small** constellation size is energy efficient at **large** transmission distance;
- **lower** target bit error probability and **large** packet size is preferred at short transmission distance, while **higher** target bit error Probability and **small** packet size is preferred at large transmission distance.

Conclusions

- For this particular constrained situation, using **maximum allowable packet length** and enough transmit power to ensure **a low retransmission number** is energy efficient.

TABLE III
CONFIGURATION TABLE WITH 10^{-2} FAULT TOLERANCE

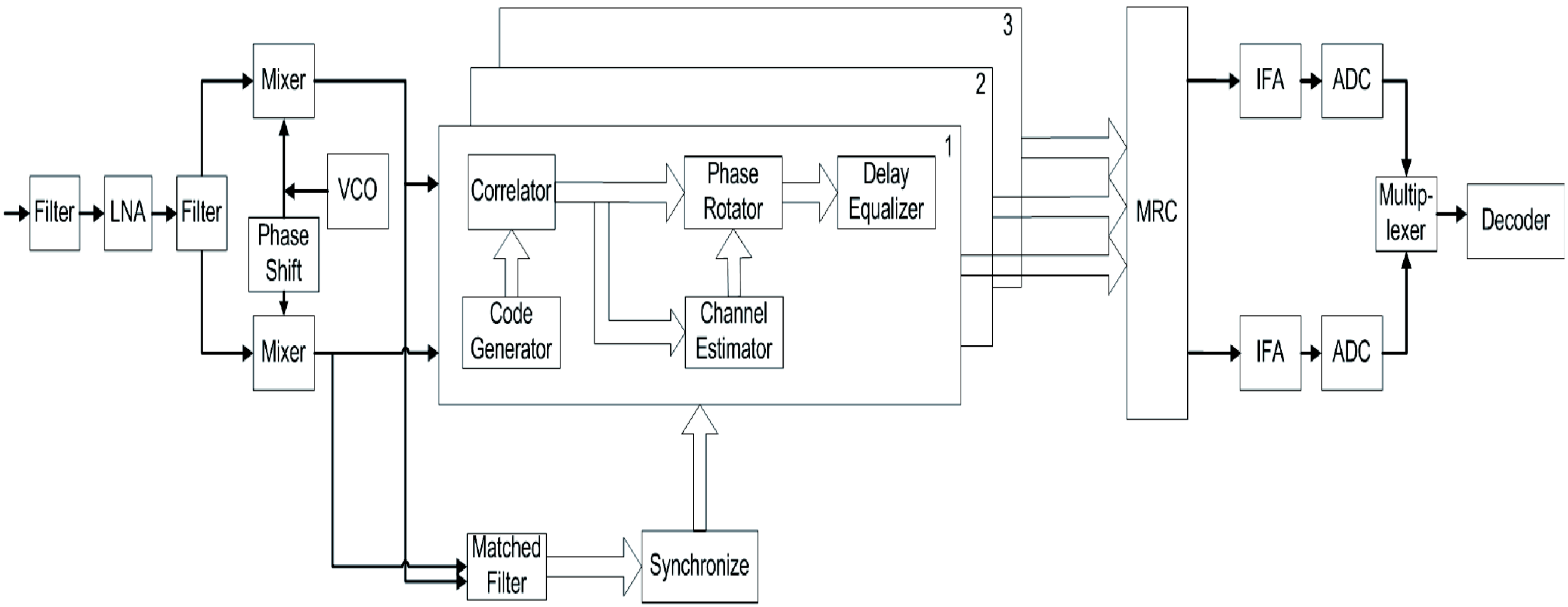
d (meters)	b (bits/symbol)	P_t (mW)	L_L^* (bytes)
$d \leq 8$	8	$146.52 \sim 206.64$	4KB
$8 < d < 12$	7	210.20	4KB
$12 \leq d < 16$	6	$203.55 \sim 244.37$	4KB
$16 \leq d < 20$	5	$217.54 \sim 253.85$	4KB
$20 \leq d < 28$	4	$212.81 \sim 312.65$	4KB
$28 \leq d < 40$	3	$228.94 \sim 386.61$	4KB
$40 \leq d < 56$	2	$235.16 \sim 393.89$	4KB
$d \geq 56$	1	$197.50 \sim 399.28$	8B $\sim$ 4KB

Current Research

- **Wideband wireless sensor network**
  - Increased bandwidth will decrease the transmission time duration, therefore introduce a possible decrease of the energy consumption;
  - However, wideband wireless channels will cause **frequency-selective fading**. In this case, a channel estimator and equalizer have to be used. This will increase the energy consumption at the receiver.
  - Moreover, the pilot symbols used in wideband communication systems will induce more overhead. This will also increase the energy consumption per information bit.

Current Research

- **Rake receiver**



Rake receiver

- Tradeoff between transmit power and diversity gain

$$\begin{aligned}\gamma(t) &= \sum_{k=1}^{M} \gamma_k(t), \\ &= \sum_{k=1}^{M} \frac{|\alpha_k(t)|^2 P_t(t)}{G_d \sigma^2}\end{aligned}$$

- Maintain a certain outage probability

$$P_a(\gamma > \gamma_0) = e^{-\gamma_0/\bar{\gamma}} \sum_{k=1}^{M} \frac{(\gamma_0/\bar{\gamma})^{k-1}}{(k-1)!}$$

Current Research

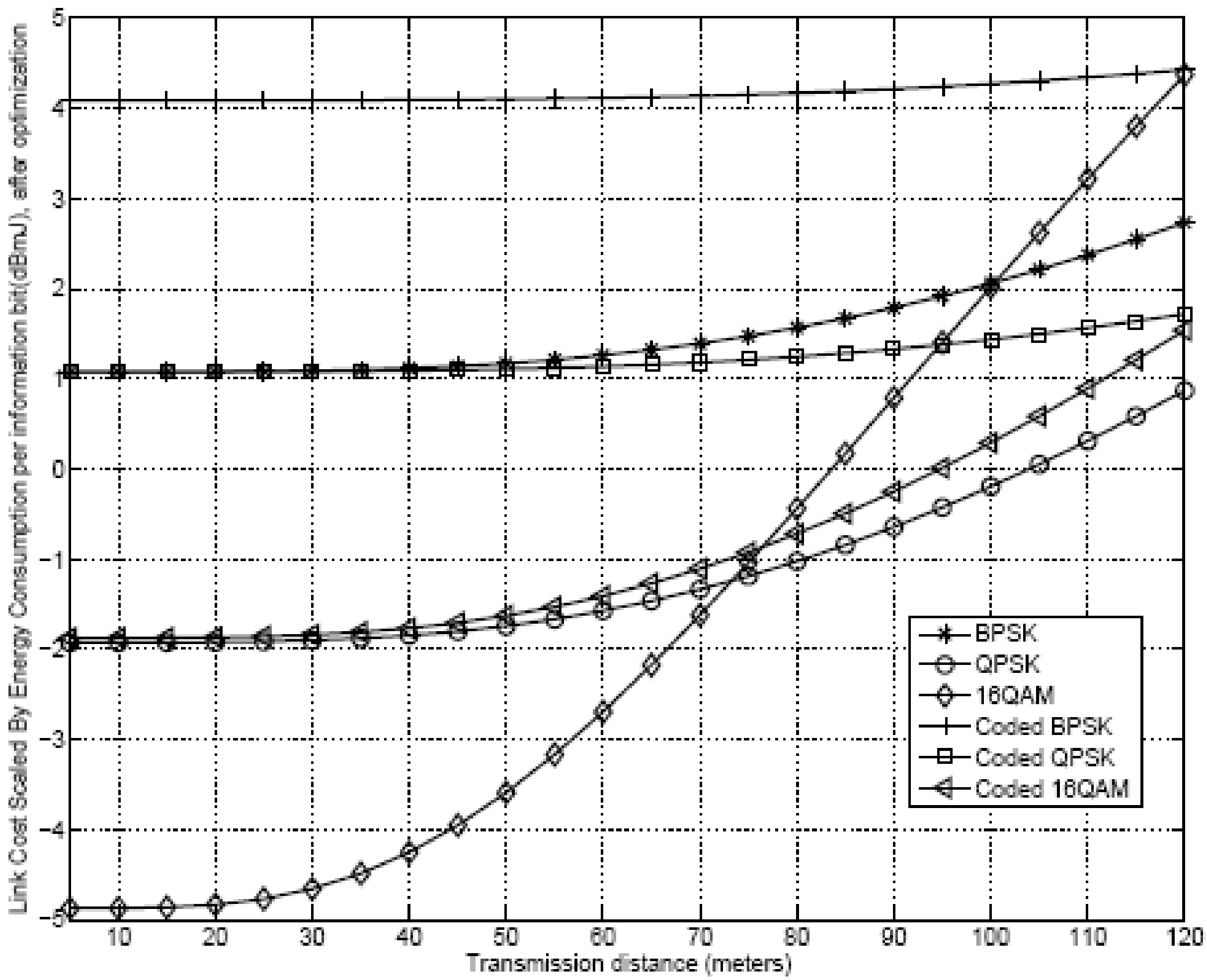
- **Application-aware/Energy-aware Link Cost**
  - Assign weights to transmit/receive energy

$$
\begin{aligned}
C_{link}(n_i, n_j)^* &= (N_{n_i} + 1)C_{total}(n_i)E_t(n_i, n_j) \\
&+ (N_{n_j} + 1)C_{total}(n_j)E_r(n_i, n_j).
\end{aligned}
$$

$$
C_{total}(n_i) = \frac{1}{E_{res}(n_i)} + \max_{(x,y)\in A(n_i)} \frac{1}{E_{cov}(x, y)}.
$$

Current Research

- Application-aware/Energy-aware Link Cost



Current Research

- Application-aware/Energy-aware Link Cost