Architecture of Wireless Sensor Networks With Mobile Sinks: Sparsely Deployed Sensors

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Outline

- Introduction
- Assumption and Problem Formulation
- System-State Model
- TSA-MSSN Algorithm and Implementation
- Simulations
- Conclusion

Introduction (1/2)

- The one-hop transmission guarantees a long lifetime for wireless sensor nodes
- The tradeoff between the probability of successful information retrieval and node energy-consumption cost is studied

Introduction (2/2)

- MSSN (Sensor Networks with Mobile Sinks) achieves
  - Simplicity in sensor-node design
  - Utilizing the higher storage/computing/communication capabilities of the sink
- TSA-MSSN
  - Transmission-Scheduling Algorithm for wireless Sensor Networks with Mobile Sinks

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Assumption and Problem Formulation (1/3)

- Assumption
  - The sink knows the position of sensor nodes and the number of packets on every node
  - We do not assume that mobility information is known at the sink in advance
  - Sink mobility (velocity and direction) would remain constant in the future
  - Only one packet can be transmitted in one time slot and that every lost packet will be retransmitted in the next assigned slot.

Assumption and Problem Formulation (2/3)

- Our Approach
  - Find the best time slots for packets transmission and use minimum transmission power for those slots
  - TSA-MSSN is a highly centralized algorithm

Assumption and Problem Formulation (3/3)

- TSA-MSSN
  - The sink runs TSA-MSSN and assigns the transmission power level to the node at the beginning of every time slot
  - The sink can piggyback the assigned transmission power level in the ACK packets, which serve to acknowledge successful or failed data transmission during the previous time slot

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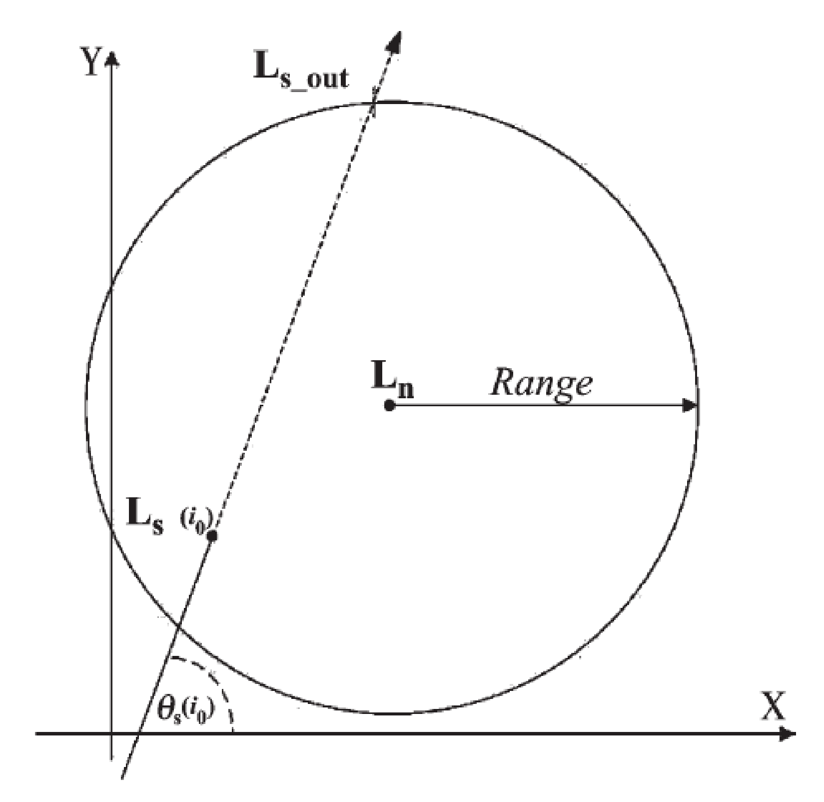
System-State Vector $\hat{\mathbf{E}}(i_0)$ (1/4)

- System state
  - $E(i_0) = \{\mathbf{L}_s(i_0), \theta_s(i_0), v_s(i_0), \mathbf{L}_n, K(i_0)\}$. (1)
- The distance between the sink and the sensor node
  - $D(i_0) = \|\mathbf{L}_s(i_0) - \mathbf{L}_n\|$ (2)
- Communication-channel gain between the sink and the sensor node
  - $G(i_0) = 10 \cdot \log(A) - 10n \cdot \log\left(D(i_0)\right) + \xi \text{ (dB)}$ (3)

System-State Vector $\hat{\mathbf{E}}(i_0)$ (2/4)

- $T(i_0)$
  - the estimated number of transmission time slots available before the sink moves out of the sensor communication range
  - $$T(i_0) = \left\lfloor \frac{\|\mathbf{L}_s(i_0) - \mathbf{L}_{s\_out}\|}{v_s(i_0) \cdot \Delta t} \right\rfloor \quad (4)$$
    - $$\Delta t = \frac{F_d + F_b}{R} \quad (5)$$
      - Duration of one time slot

System-State Vector $\hat{\mathbf{E}}(i_0)$ (3/4)



System-State Vector $\hat{\mathbf{E}}(i_0)$ (4/4)

- The series of estimated states
  - $$\hat{\mathbf{E}}(i_0) = \left[\hat{E}(i_0), \hat{E}(i_0+1), \ldots, \hat{E}\left(i_0 + T(i_0) + 1\right)\right] \quad (6)$$

    $$\hat{E}(i_0) = E(i_0) \quad (7)$$

  - $\forall i \in \{i_0, \ldots, i_0 + T(i_0) + 1\}$

    $$\begin{cases} \hat{\mathbf{L}}_s(i) = \mathbf{L}_s(i_0) + (i - i_0) \cdot v_s \cdot \Delta t \cdot [\cos(\theta_s), \sin(\theta_s)] \\ \hat{\theta}_s(i) = \theta_s; \hat{v}_s(i) = v_s \end{cases} \quad (8)$$

Markov-Chain Model of $\hat{\mathrm{E}}(i_0)$ (1/2)

- The transmission strategy is decided by $P_t(i)$, which is the transmission power at the sensor node (and could be zero if the strategy is to sleep during that slot)
- Given $\hat{E}(i)$ and $P_t(i)$, $\hat{E}(i + 1)$ is not related to any previous states before i. Thus, $\{\hat{E}(i)\}$ can be modeled as a Markov chain in time domain

$$\mathrm{Prob}\left(\hat{E}(i+1)|\hat{E}(i_0),\ldots,\hat{E}(i),P_t(i_0),\ldots,P_t(i)\right) = \mathrm{Prob}\left(\hat{E}(i+1)|\hat{E}(i),P_t(i)\right). \quad (9)$$

Markov-Chain Model of $\hat{\mathbf{E}}(i_0)$ (2/2)

- State-transferring probability function

$$\mathrm{Prob}\left(\hat{E}(i+1)|\hat{E}(i), P_t(i)\right) = \begin{cases} \mathrm{P\hat{E}R}(i), & \hat{K}(i+1) = \hat{K}(i) \\ 1 - \mathrm{P\hat{E}R}(i), & \hat{K}(i+1) = \hat{K}(i) - 1 \\ 0, & \text{otherwise} \end{cases} \quad (10)$$

$$\mathrm{P\hat{E}R}(i) = 1 - \left(1 - Q\left(\sqrt{\frac{2P_t(i)\cdot\hat{G}(i)}{\sigma_n^2}}\right)\right)^{F_d} \quad (11)$$

$$Q(x) = (1/\sqrt{\pi})\cdot\int_{(x/\sqrt{2})}^{\infty} e^{-t^2}dt, \ \hat{G}(i) = A\cdot\hat{D}(i)^{-n} \quad (12)$$

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TSA-MSSN Algorithm and Implementation

- TSA-MSSN
  - the objective of TSA-MSSN is to decide the optimal strategy $P_t{*}\,(E(i_0))$ that maximizes the probability of successful transmission and, at the same time, minimizes the energy consumption. However, these two objectives cannot be achieved simultaneously
  - $$P_t^*\left(E(i_0)\right) = \arg\max_{P_t(i_0)} \left\{ J\left(P_t(i_0), \hat{E}(i_0) \right) \right\} \quad (13)$$

Recursive Design of Utility Functions (1/3)

- Given $J(P_t(i+1), \hat{E}(i+1))$, design the utility function $J(P_t(i), \hat{E}(i))$
- We define $$U\left(\hat{E}(i)\right) = \max_{P_t(i)} \left\{ J\left(P_t(i), \hat{E}(i)\right) \right\} \quad (14)$$
- $$J\left(P_t(i), \hat{E}(i)\right) = J_m\left(P_t(i), \hat{E}(i)\right) - J_c\left(P_t(i)\right) \quad (15)$$
  - *Jm*($P_t(i)$, ˆ*E* (*i*)) is the figure of credit which denotes the expected achievable utility credit by adopting strategy $P_t(i)$ at state ˆ*E* (*i*). Successful transmission credit
  - The $J_c(P_t(i))$ is the figure of cost, which is determined by the energy consumption associated with $P_t(i)$.

Recursive Design of Utility Functions (2/3)

- $$J_m\left(P_t(i), \hat{E}(i)\right) = \sum_{\hat{E}(i+1)} U\left(\hat{E}(i+1)\right) \cdot \text{Prob}\left(\hat{E}(i+1) | P_t(i), \hat{E}(i)\right) \quad (16)$$

- $$J_c\left(P_t(i)\right) = \frac{\lambda}{\max\{P_t\}} \cdot P_t(i) \quad (17)$$

  - λ is a weight coefficient indicating the tradeoff between successful transmission credit and energy-consumption cost .

Recursive Design of Utility Functions (3/3)

- Combining previous formulations, we get

$$J\left(P_t(i), \hat{E}(i)\right) = \sum_{\hat{E}(i+1)} \max_{P_t(i+1)} \left\{ J\left(P_t(i+1), \hat{E}(i+1)\right) \right\} \cdot \mathrm{Prob}\left(\hat{E}(i+1) | P_t(i), \hat{E}(i)\right) - \frac{\lambda}{\max\{P_t\}} \cdot P_t(i). \quad (18)$$

Final-State Configuration Application

- when $i = i_0 + T(i_0) + 1$, the J_c is zero for all system states, since there will be no active transmission and, therefore, $P_t(i_0 + T(i_0) + 1) = 0$.

$$
\begin{aligned}
J&\left(P_t\left(i_0+T(i_0)+1\right),\hat{E}\left(i_0+T(i_0)+1\right)\right)\\
&=J_m\left(P_t\left(i_0+T(i_0)+1\right),\hat{E}\left(i_0+T(i_0)+1\right)\right)\\
&=J_m\left(\hat{E}\left(i_0+T(i_0)+1\right)\right).
\end{aligned}
\tag{19}
$$

Final-State Configuration Application – Scenario *I*

- Assume
  - Every $K(i_0)$ packet is of the same credit
- The number of successfully transmitted packets

$$J_m\left(\hat{E}\left(i_0+T(i_0)+1\right)\right)=K(i_0)-\hat{K}\left(i_0+T(i_0)+1\right) \qquad (20)$$

- If we want to set $J_c(\alpha\cdot\max\{P_t\})=1$, then

$$\lambda(\alpha)=\arg_{\lambda}\left\{J_c\left(\alpha\cdot\max\{P_t\}\right)=1\right\} \qquad (21)$$

$$=\frac{1}{\alpha} \qquad 0<\alpha<1$$

【According to (17)】

Final-State Configuration Application – Scenario *II* (1/2)

- Assume
  - The integrity of all $K(i_0)$ packets is essential (22)

$$J_m\left(\hat{E}\left(i_0+T(i_0)+1\right)\right)=\begin{cases}1, \hat{K}\left(i_0+T(i_0)+1\right)=0\\0, \hat{K}\left(i_0+T(i_0)+1\right)\neq 0\end{cases}$$

- Placing $\lambda=1/(T(i_0)+1)$ implies that the credit of successful transmission equals the cost of the average transmission power $P_{avg}(i_0)=\max\{P_t\}$

$$P_{\mathrm{avg}}(i_0)=\frac{1}{T(i_0)+1}\cdot\sum_{i=i_0}^{i_0+T(i_0)}P_t^*\left(\hat{E}(i)\right). \qquad (23)$$

Final-State Configuration Application – Scenario *II* (2/2)

- If we want to have

$$(T(i_0)+1)\cdot J_c(\alpha\cdot\max\{P_t\})=1$$

, then

$$\lambda(\alpha)=\arg_\lambda\{(T(i_0)+1)\cdot J_c(\alpha\cdot\max\{P_t\})=1\}$$
$$=\frac{1}{\alpha\cdot\{T(i_0)+1\}}. \quad (24)$$

【According to (17)】

$0<\alpha<1$

Summary (1/2)

Given $E(i_0) = \{\mathbf{L_s}(i_0), \theta_s(i_0), v_s(i_0), \mathbf{L_n}, K(i_0)\}$;

Calculate $T(i_0)$ **by** Eq. (4):

$$T(i_0) = \left\lfloor \frac{\|\mathbf{L_s}(i_0) - \mathbf{L_{s\_out}}\|}{v_s(i_0) \cdot \Delta t} \right\rfloor,$$

where $\mathbf{L_{s\_out}}$ **is given in Appendix I;**

Define the final-state configuration function Eq.(19)

$$J\left(P_t(i_0 + T(i_0) + 1), \hat{E}(i_0 + T(i_0) + 1)\right) = J_m\left(\hat{E}(i_0 + T(i_0) + 1)\right),$$

by Eq. (20) **or** Eq. (22), etc.;

For $i = i_0 + T(i_0)$ **down to** i_0,

For all $\hat{E}(i) = \left\{\hat{\mathbf{L_s}}(i), \theta_s, v_s, \mathbf{L_n}, \hat{K}(i)\right\}$,

Calculate $J\left(P_t(i), \hat{E}(i)\right)$ **by** Eq.(18):

$$J\left(P_t(i), \hat{E}(i)\right) = \sum_{\hat{E}(i+1)} \max_{P_t(i+1)} \left\{J\left(P_t(i+1), \hat{E}(i+1)\right)\right\} \cdot Prob\left(\hat{E}(i+1) | P_t(i), \hat{E}(i)\right) - \frac{\lambda}{\max\{P_t\}} \cdot P_t(i);$$

End for

End for

Decide the optimal transmission strategy by Eq. (13):

$$P_t^*(E(i_0)) = \arg\max_{P_t(i_0)} \left\{J\left(P_t(i_0), \hat{E}(i_0)\right)\right\}.$$

Summary (2/2)

- Number of table entries N_t

$$N_t < \sum_{k=1}^{N_v} \left\lceil \frac{2 \cdot \text{Range}}{k \cdot \Delta v \Delta t} \right\rceil \cdot \left\lceil \frac{\pi \cdot \text{Range}^2}{\Delta S} \right\rceil \quad (25)$$

  - The maximum number of packets : $\left\lceil \frac{2 \cdot \text{Range}}{k \cdot \Delta v \Delta t} \right\rceil$
  - The number of grids for L_n : $\left\lceil \frac{\pi \cdot \text{Range}^2}{\Delta S} \right\rceil$
  - The number of discrete values for $v_s(i_0)$: N_v

$$N_v = \lceil v_{\max} / \Delta v \rceil$$

  - Range = 50m, V_{max} = 30m/s, Δv = 1m/s, ΔS = 1m^2, F_d = 128*8bits, F_b = 20*8bits, R = 20kb/s,
    → $N_t < 53 \times 10^6$

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Simulations

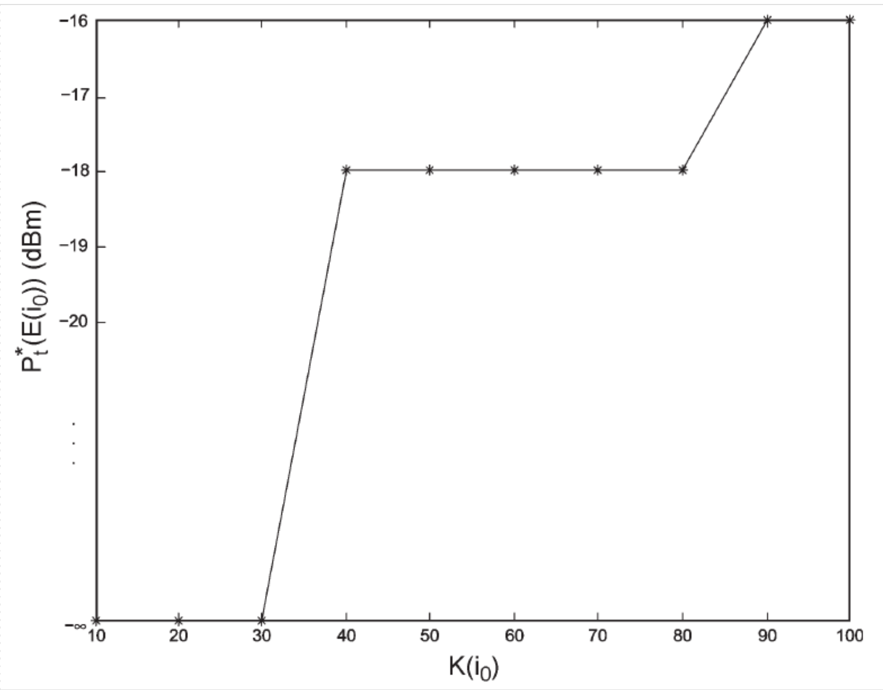
- Assume
  - the sink is installed in a car which is driven along the highway
  - the sensor nodes are deployed along the highway
  - IEEE 802.15.4
  - $$P_t(i) \in \{-\infty, -32, -28, -24, -20, -18, -16, -14, -12, -10, -8, -6, -4, -2, 0\} \text{ (dBm)} \quad (26)$$

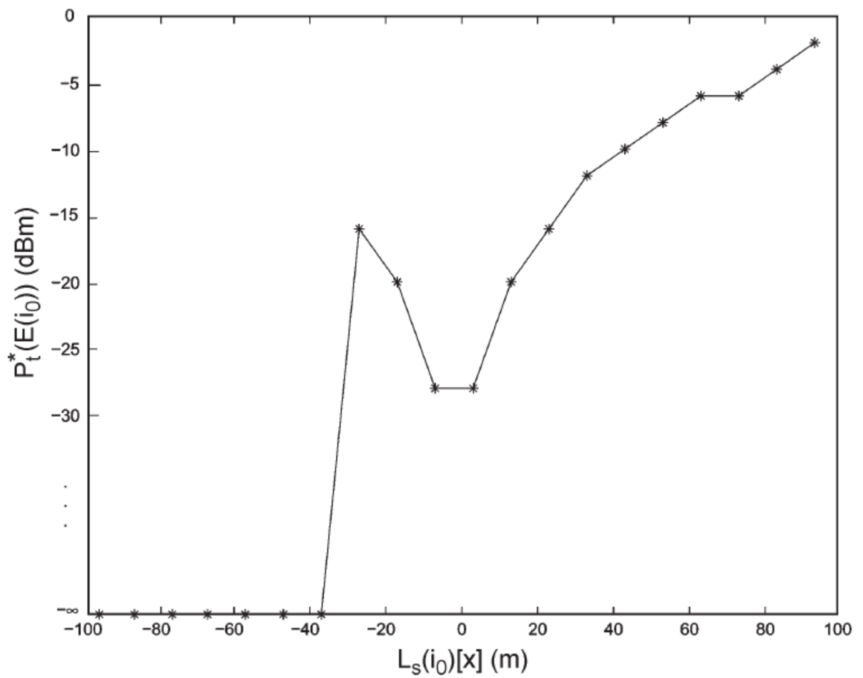
Parameter	Unit	Value
F_d	bit	128×8
F_b	bit	20×8
R	$bits/sec$	20000
n		2.5
A	dB	-31
ξ	dB	$N\left(0, \sigma_\xi^2\right)$
$Range$	m	100
σ_n^2	dBm	-92
$v_s(i)$	m/sec	20

Transmission Scheduling in TSA-MSSN – Application Scenario *I*

- First, We Fix $L_n = k[0, 0]$, $\theta_s(i0) = 0$, $L_s(i_0) = [-20, 10]$, $\lambda = 1$

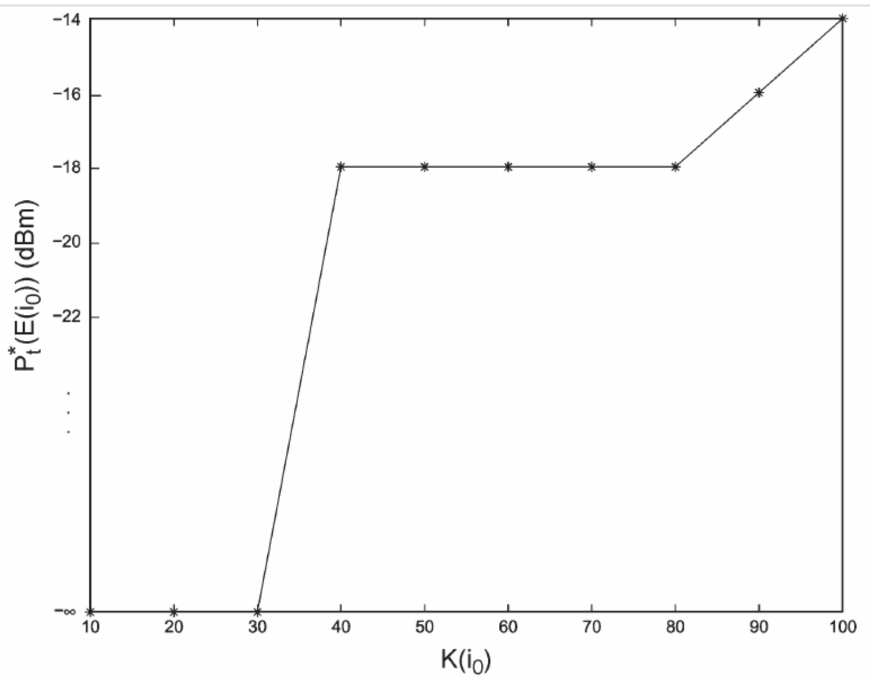
- Move the location of the sink $Ls(i0)$ along the map from [−97, 5] to [97, 5] and fix $K(i_0) = 50$

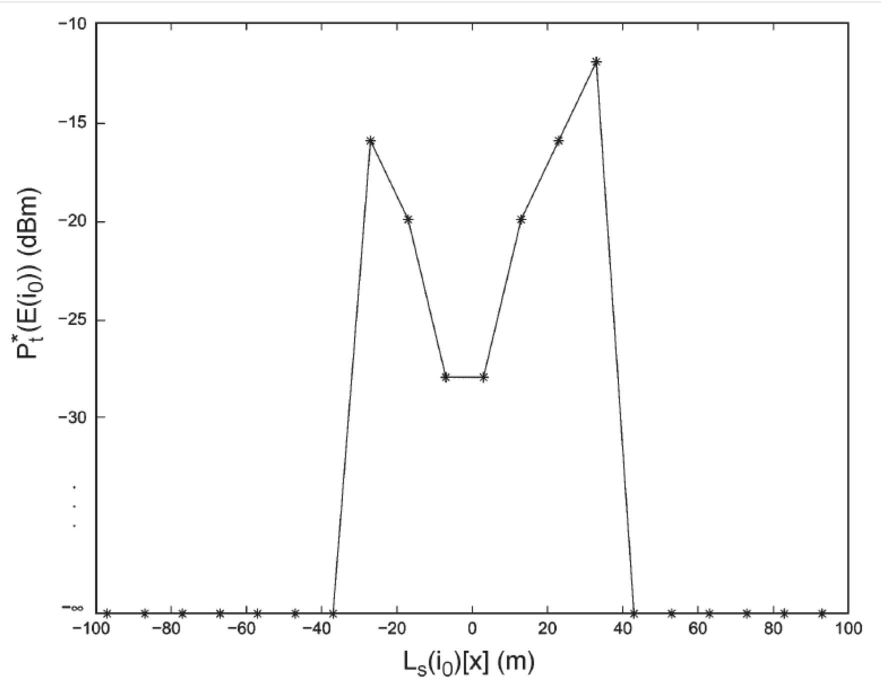




Transmission Scheduling in TSA-MSSN – Application Scenario *II*

- First, We Fix $L_n = k[0, 0]$, $\theta_s(i0) = 0$, $L_s(i_0) = [-20, 10]$, $\alpha = 1$
- Move the location of the sink $Ls(i0)$ along the map from [−97, 5] to [97, 5] and fix $K(i_0) = 50$



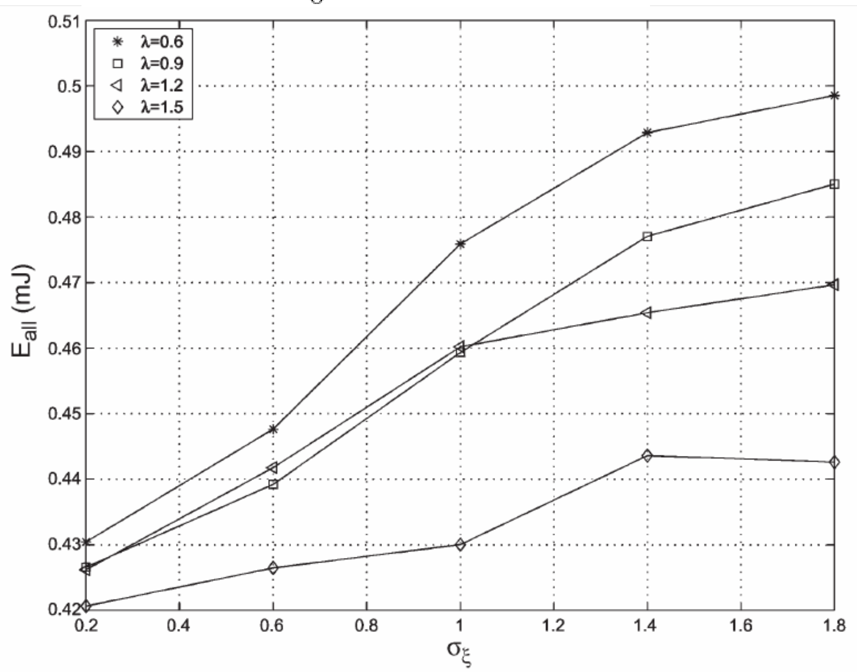


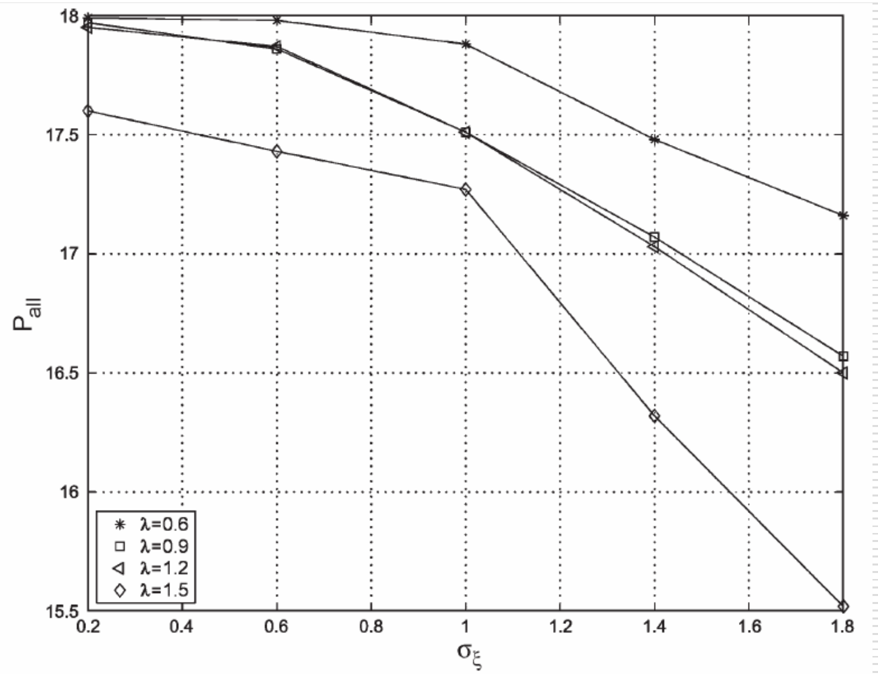
Real-World Simulations - Application Scenario *I*

- L_n = [0, 0], $\theta_s(i0)$ = 0, $K(i_0)$ = 18, $L_s(i_0)$ = [75, 10]
- E_{all} : total energy consumption
- P_{all} : number of successfully transmitted packets

$$E_{\text{all}} = \sum_{i=i_0}^{i_0+T(i_0)} P_t^*\left(E(i)\right) \cdot \frac{F_d}{R} \quad (27)$$

$$P_{\text{all}} = K(i_0) - K\left(i_0 + T(i_0) + 1\right) \quad (28)$$

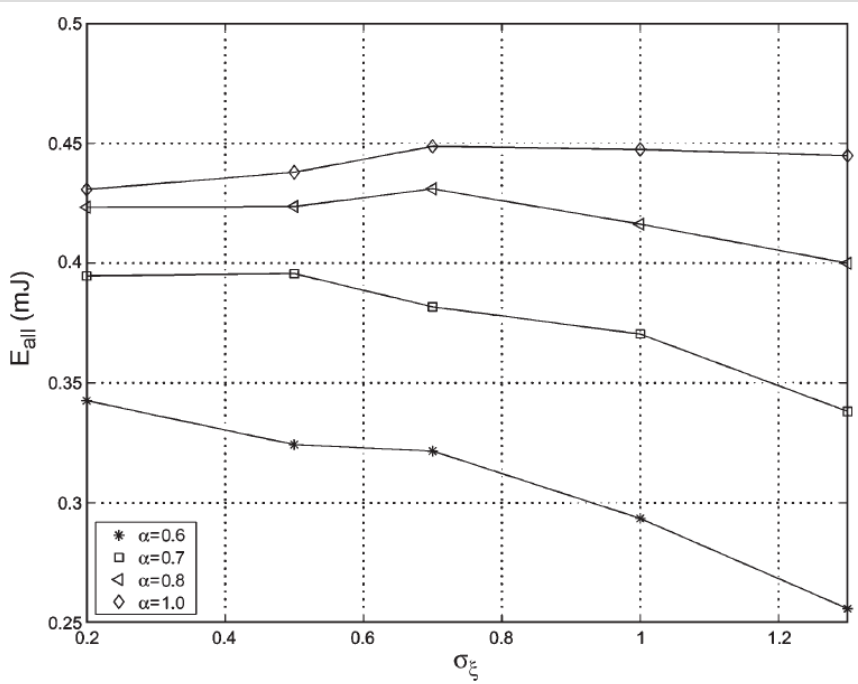


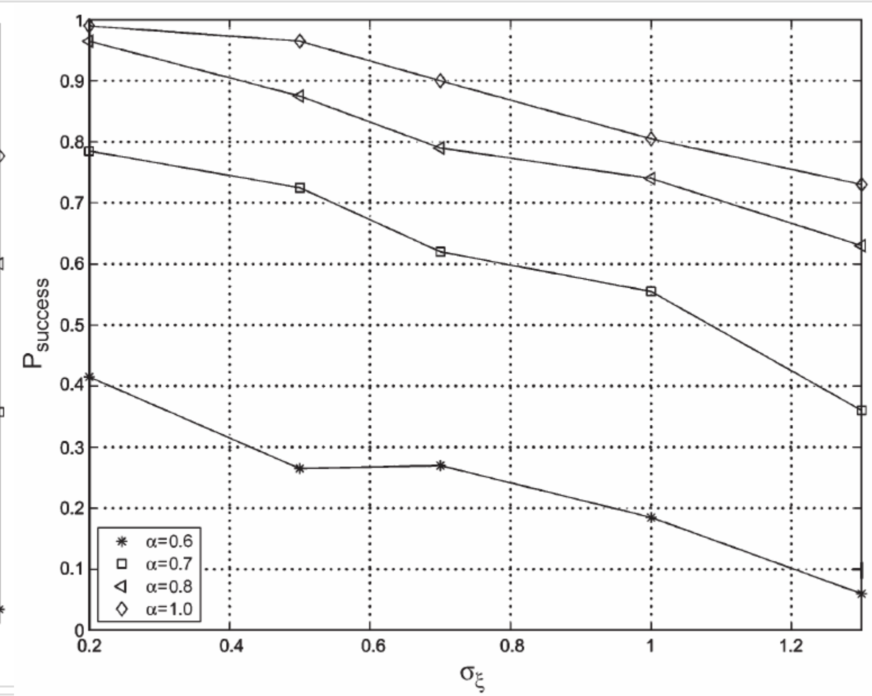


Real-World Simulations - Application Scenario *II*

- E_{all} : total energy consumption
- $P_{success}$: ratio of successfully transmission

$$P_{\text{success}} = \begin{cases} 1, & K\left(i_0 + T(i_0) + 1\right) = 0 \\ 0, & K\left(i_0 + T(i_0) + 1\right) > 0 \end{cases} \tag{29}$$





Conclusion

- We have proposed an architecture of wireless MSSN.
- In the design of the TSA-MSSN, a coefficient λ has been employed to control the tradeoff between the credit of successful transmission retrieval and the cost of energy consumption.
- The results can possibly lead to an MSSN network deployment for highway-traffic-surveillance applications.
- The final-state configuration decides the packet scheduling at the MSSN to-sink unicast module.