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Optimal Resource Allocation for Pervasive Health Monitoring Systems with Body Sensor Network

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Outline

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- Problem Statement
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- QoS Optimization Problem
- Simulation
- Conclusion

Introduction

- E-Health, (integrates information processing and communication technologies into traditional medical services), helps to improve healthcare efficiency.
- Pervasive health monitoring is an E-Health service.

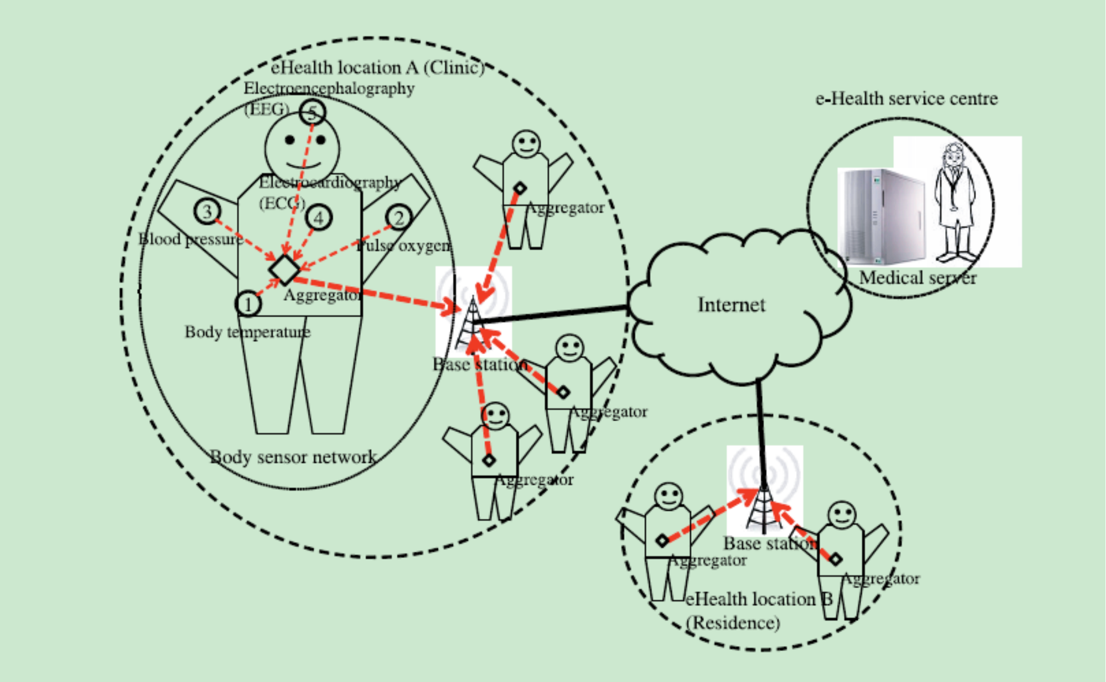


Fig. 1. A pervasive health monitoring system with body sensor networks.

Two challenges in pervasive health monitoring systems with BSN:

1. The sustainable power supply for body sensor network. (battery—energy harvesting, scavenging)
2. QoS guarantee for the delivery of data streams. (different priorities)

This paper optimizes the resource allocation in the health monitoring system to provide a sustainable and high-quality service to subscribers.

Problem Statement

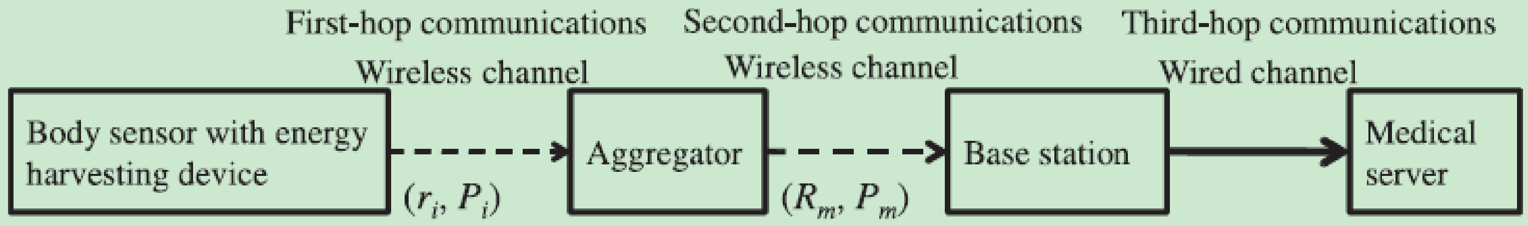


Fig. 2. Transmission path of data streams in the health monitoring system.

- Objective of health monitoring systems: To provide a sustainable and high-quality service to subscribers.
- Sustainable: run without interrruption
- The factors of a high-quality service:

1) the source rate from a sensor (fidelity)
2) the packet loss rate(PLR) and the delay of the data stream over the transmission path. (QoS metrics)

Two Trade-Offs in Health Monitoring System

- 1. interdependence between the sustainability and the high quality.
- The paper examined this trade-off in the steady –rate optimization problem. Optimize the source rate at each sensor with energy harvesting device to guarantee an uninterrupted service.
- 2. interdependence between the source rate and the QoS.   (congestions, transmission error)
- QoS optimization problem, jointly optimize the transmission rate and the transmission power at each aggregator to provide QoS guarantees to the data delivery

Steady-Rate Optimization Problem

- Source rate & the lifetime of the sensor (limited battery capacity, energy harvesting device)
  -dynamic energy replenishment, adjust source rate.
- The steady-rate optimization problem: minimizes the rate fluctuation under the constraints of the uninterrupted service.
- Difference of BSN to other wireless sensor network.

Critical readings should be treated with a higher priority.

Differentiated treatment: packet classification & packet scheduling

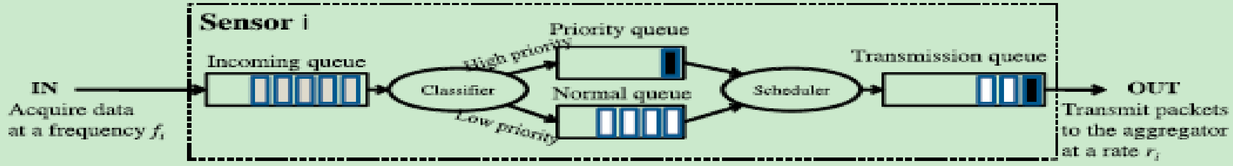


Fig. 3. Packet classification and packet scheduling at a sensor.

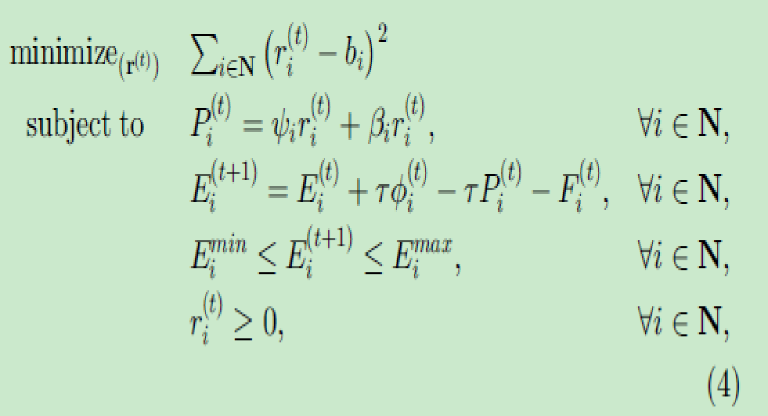
System models

- 1. Energy Harvesting Model:
- can be modeled as discrete-time Markov chain $\{A_i, Q_i\}$;
- Π_i denote the steady-probability vector at sensor i, $\Pi_i^T Q_i = \Pi_i^T$, and $\Pi_i^T I = 1$
- 2. Power Consumption Model
- Sensing power consumption & transmission power consumption.
- $P_{s,i} = \psi_i r_i$, r_i: *source rate*. (Sensing power consumption)
- $P_{t,i} = \beta_i r_i$
- $P_i = P_{s,i} + \mathrm{P}_{\mathrm{t,i}}$

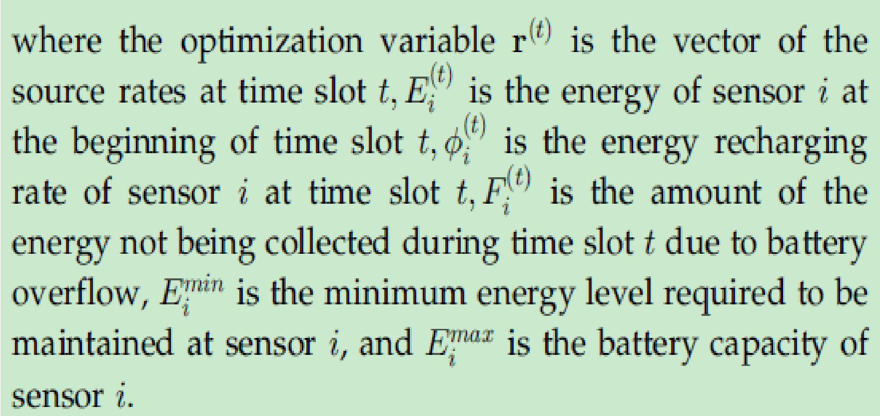
Source rate and uninterrupted lifetime of the sensor

- Theorem 1: the initial energy is E_i^{ini} of sensor i.
- 1) if $0 < r_i \leq \frac{g_i^{(1)}}{\psi_i+\beta_i}$, Never run out…
- 2) if $r_i > \frac{g_i^{|A_i|}}{\psi_i+\beta_i}$, will run out at certain time.

Steady-Rate Optimization Problem

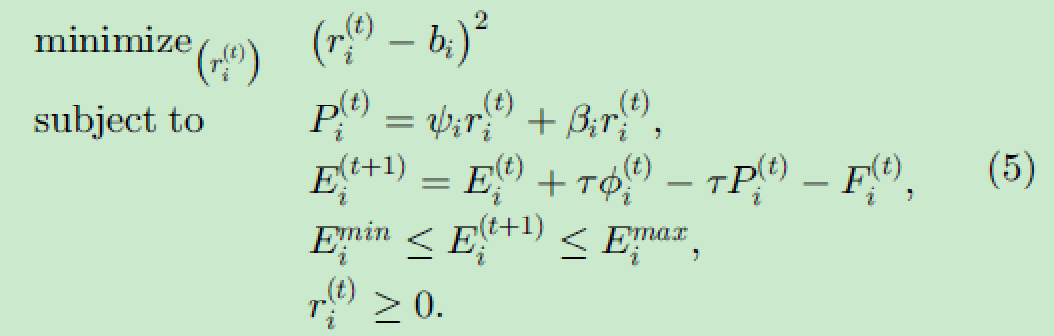
- Define the average sustainable rate b_i of sensor i as the source rate, at which sensor i will consume the same energy as the harvest energy in a long run.
- $g_i^{avg} = \psi_i b_i + \beta_i b_i$, then get b_i.
- 

$$\begin{aligned} \text{minimize}_{(\mathbf{r}^{(t)})} \quad & \textstyle\sum_{i\in \mathrm{N}} \left(r_i^{(t)} - b_i\right)^2 && \\ \text{subject to} \quad & P_i^{(t)} = \psi_i r_i^{(t)} + \beta_i r_i^{(t)}, && \forall i \in \mathrm{N}, \\ & E_i^{(t+1)} = E_i^{(t)} + \tau\phi_i^{(t)} - \tau P_i^{(t)} - F_i^{(t)}, && \forall i \in \mathrm{N}, \\ & E_i^{min} \le E_i^{(t+1)} \le E_i^{max}, && \forall i \in \mathrm{N}, \\ & r_i^{(t)} \ge 0, && \forall i \in \mathrm{N}, \end{aligned} \tag{4}$$



where the optimization variable $\mathbf{r}^{(t)}$ is the vector of the source rates at time slot t, $E_i^{(t)}$ is the energy of sensor i at the beginning of time slot t, $\phi_i^{(t)}$ is the energy recharging rate of sensor i at time slot t, $F_i^{(t)}$ is the amount of the energy not being collected during time slot t due to battery overflow, E_i^{min} is the minimum energy level required to be maintained at sensor i, and E_i^{max} is the battery capacity of sensor i.

Optimal analytical solution



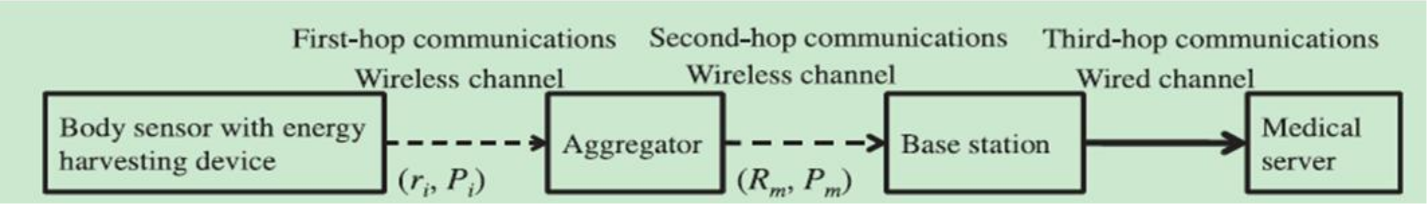
$$\begin{aligned} &\text{minimize}_{\left(r_i^{(t)}\right)} && \left(r_i^{(t)} - b_i\right)^2 \\ &\text{subject to} && P_i^{(t)} = \psi_i r_i^{(t)} + \beta_i r_i^{(t)}, \\ & && E_i^{(t+1)} = E_i^{(t)} + \tau\phi_i^{(t)} - \tau P_i^{(t)} - F_i^{(t)}, \qquad (5) \\ & && E_i^{min} \le E_i^{(t+1)} \le E_i^{max}, \\ & && r_i^{(t)} \ge 0. \end{aligned}$$

- Case 1: If $\phi_i^{(t)} < g_i^{avg}$
- 1.1 if $E_i^{(t)} - E_i^{min} \ge \tau(g_i^{avg} - \phi_i^{(t)})$, the optimal source rate $r_i^{(t)^*} = b_i$
- 1.2 if $E_i^{(t)} - E_i^{min} < \tau(g_i^{avg} - \phi_i^{(t)})$, the optimal source rate $r_i^{(t)^*} = \frac{E_i^{(t)} - E_i^{min} + \tau\phi_i^{(t)}}{\tau(\psi_i + \beta_i)}$

- Case 2: If $\phi_i^{(t)} \ge g_i^{avg}$
- 1.1 if $E_i^{max} - E_i^{(t)} \ge \tau(\phi_i^{(t)} - g_i^{avg})$, the optimal source rate $r_i^{(t)^*} = b_i$
- 1.2 if $E_i^{max} - E_i^{(t)} < \tau(\phi_i^{(t)} - g_i^{avg})$, the optimal source rate $r_i^{(t)^*} = b_i$

QoS Optimization Problem

- In health monitoring systems, a loss or an excessive delay of the prioritized data may cause a fatal accident.



- Study the QoS optimization problem on the second-hop communications.

System Models

- Queuing model
- the aggregator aggregates the packets from all the body sensors. The arrival of the packets follow a Poisson process with a rate $\lambda_m^{(t)}$;
- $\lambda_m^{(t)} = \lambda_{P,m}^{(t)} + \lambda_{N,m}^{(t)}$; P: priority packets, N: normal packets
- the service rate at aggregator m at time slot t is denoted by $\mu_m^{(t)}$; $\mu_m^{(t)} = R_m^{(t)}/L_m$, where L_m: average packet length; $R_m^{(t)}$ transmission rate.
- M/M/1 queuing system to be stable, need to satisfy:

$$\lambda_{N,m}^{(t)} + \lambda_{P,m}^{(t)} \leq u_m^{(t)}, \quad \forall m \in \mathbf{M}, \tag{6}$$

QoS metrics

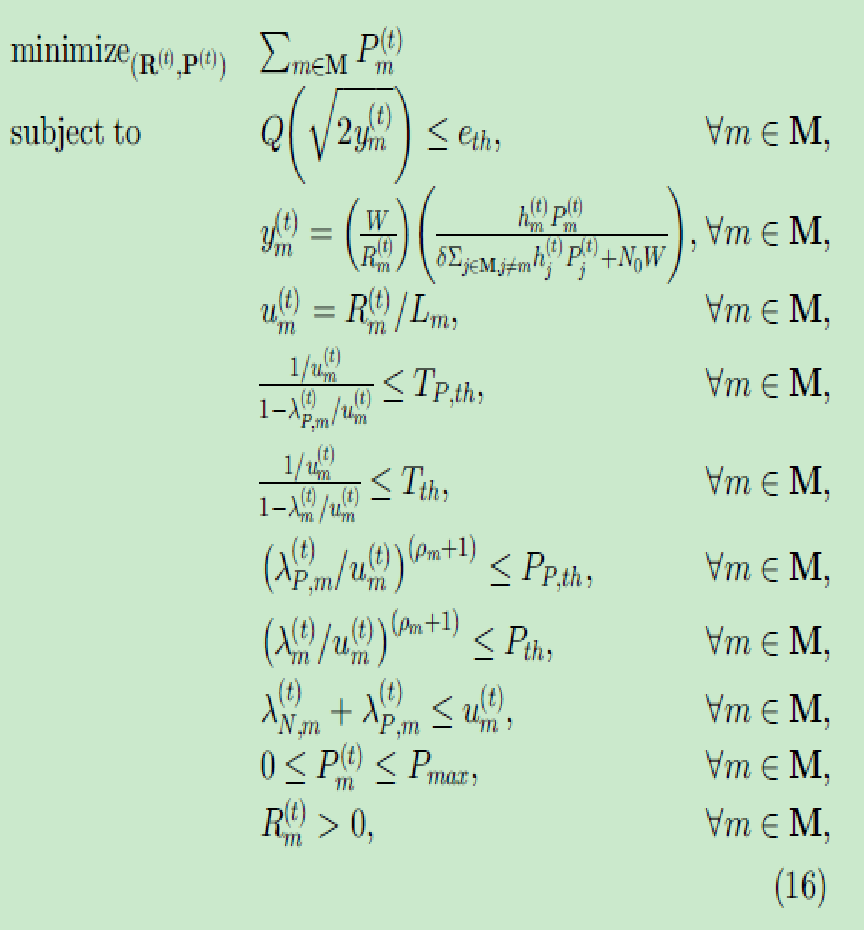
- Path Loss Rate(PLR) & the delay of the Prioritized packets and all the packets.
- PLR consists of congestion PLR due to queue overflow and the transmission PLR due to transmission error.

$$
\begin{aligned}
P_{P,m}^{PLR} &= 1 - \left(1 - P_{P,m}^{c}\right)\left(1 - P_{m}^{e}\right) \\
&= 1 - \left(1 - \left(\frac{\lambda_{P,m}^{(t)}}{u_{m}^{(t)}}\right)^{(\rho_m+1)}\right)\left(1 - Q\left(\sqrt{2y_{m}^{(t)}}\right)\right)^{L_m}, \quad (14) \\
&\forall m \in \mathbf{M}.
\end{aligned}
$$

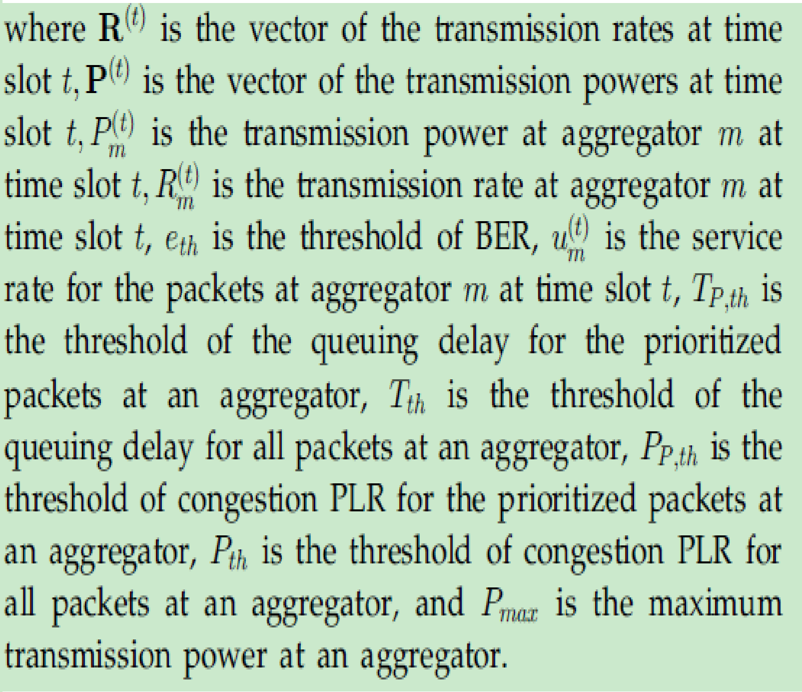
$$
\begin{aligned}
P_{m}^{PLR} &= 1 - \left(1 - P_{m}^{c}\right)\left(1 - P_{m}^{e}\right) \\
&= 1 - \left(1 - \left(\frac{\lambda_{m}^{(t)}}{u_{m}^{(t)}}\right)^{(\rho_m+1)}\right)\left(1 - Q\left(\sqrt{2y_{m}^{(t)}}\right)\right)^{L_m}, \quad (15) \\
&\forall m \in \mathbf{M}.
\end{aligned}
$$

- The delay consists of the queuing delay and propagation delay(can be neglected).

QoS optimization Problem



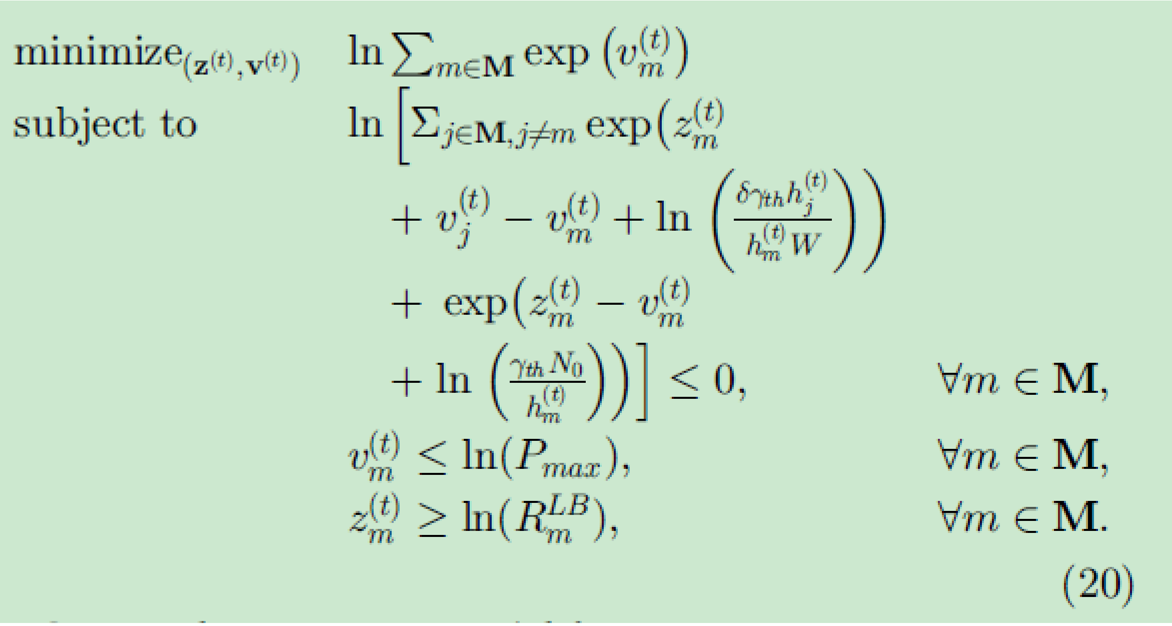
$$\begin{array}{lll}
\text{minimize}_{(\mathbf{R}^{(t)},\mathbf{P}^{(t)})} & \sum_{m\in\mathbf{M}} P_m^{(t)} & \\
\text{subject to} & Q\left(\sqrt{2y_m^{(t)}}\right) \le e_{th}, & \forall m \in \mathbf{M}, \\
& y_m^{(t)} = \left(\frac{W}{R_m^{(t)}}\right)\left(\frac{h_m^{(t)}P_m^{(t)}}{\delta\Sigma_{j\in\mathbf{M},j\neq m} h_j^{(t)}P_j^{(t)} + N_0 W}\right), & \forall m \in \mathbf{M}, \\
& u_m^{(t)} = R_m^{(t)}/L_m, & \forall m \in \mathbf{M}, \\
& \frac{1/u_m^{(t)}}{1-\lambda_{P,m}^{(t)}/u_m^{(t)}} \le T_{P,th}, & \forall m \in \mathbf{M}, \\
& \frac{1/u_m^{(t)}}{1-\lambda_m^{(t)}/u_m^{(t)}} \le T_{th}, & \forall m \in \mathbf{M}, \\
& \left(\lambda_{P,m}^{(t)}/u_m^{(t)}\right)^{(\rho_m+1)} \le P_{P,th}, & \forall m \in \mathbf{M}, \\
& \left(\lambda_m^{(t)}/u_m^{(t)}\right)^{(\rho_m+1)} \le P_{th}, & \forall m \in \mathbf{M}, \\
& \lambda_{N,m}^{(t)} + \lambda_{P,m}^{(t)} \le u_m^{(t)}, & \forall m \in \mathbf{M}, \\
& 0 \le P_m^{(t)} \le P_{max}, & \forall m \in \mathbf{M}, \\
& R_m^{(t)} > 0, & \forall m \in \mathbf{M},
\end{array} \tag{16}$$



where $\mathbf{R}^{(t)}$ is the vector of the transmission rates at time slot t, $\mathbf{P}^{(t)}$ is the vector of the transmission powers at time slot t, $P_m^{(t)}$ is the transmission power at aggregator m at time slot t, $R_m^{(t)}$ is the transmission rate at aggregator m at time slot t, e_{th} is the threshold of BER, $u_m^{(t)}$ is the service rate for the packets at aggregator m at time slot t, $T_{P,th}$ is the threshold of the queuing delay for the prioritized packets at an aggregator, T_{th} is the threshold of the queuing delay for all packets at an aggregator, $P_{P,th}$ is the threshold of congestion PLR for the prioritized packets at an aggregator, P_{th} is the threshold of congestion PLR for all packets at an aggregator, and P_{max} is the maximum transmission power at an aggregator.

Convex optimization

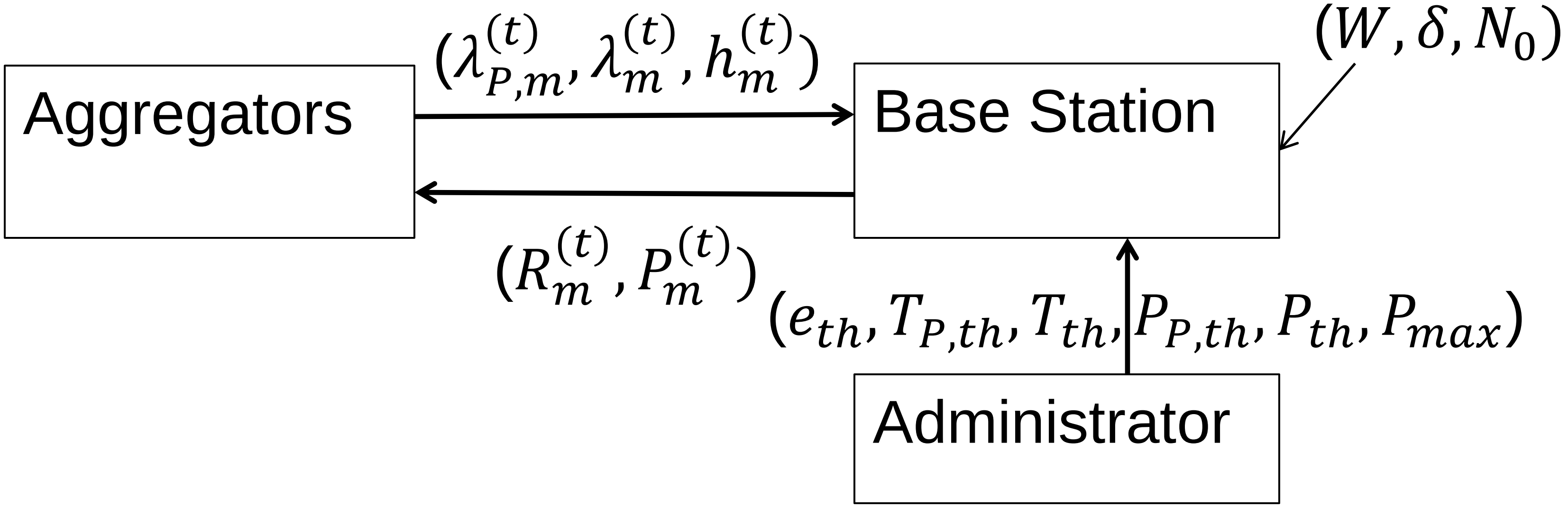
- The QoS optimization problem (17) after some convertions can be transformed into a convex optimization problem.



$$
\begin{aligned}
\text{minimize}_{(\mathbf{z}^{(t)},\mathbf{v}^{(t)})} \quad & \ln \textstyle\sum_{m\in\mathbf{M}} \exp\left(v_m^{(t)}\right) \\
\text{subject to} \quad & \ln \Big[\textstyle\sum_{j\in\mathbf{M}, j\neq m} \exp\Big(z_m^{(t)} \\
& \quad + v_j^{(t)} - v_m^{(t)} + \ln\Big(\frac{\delta\gamma_{th} h_j^{(t)}}{h_m^{(t)} W}\Big)\Big) \\
& \quad + \exp\Big(z_m^{(t)} - v_m^{(t)} \\
& \quad + \ln\Big(\frac{\gamma_{th} N_0}{h_m^{(t)}}\Big)\Big)\Big] \leq 0, && \forall m \in \mathbf{M}, \\
& v_m^{(t)} \leq \ln(P_{max}), && \forall m \in \mathbf{M}, \\
& z_m^{(t)} \geq \ln(R_m^{LB}), && \forall m \in \mathbf{M}.
\end{aligned}
\tag{20}
$$

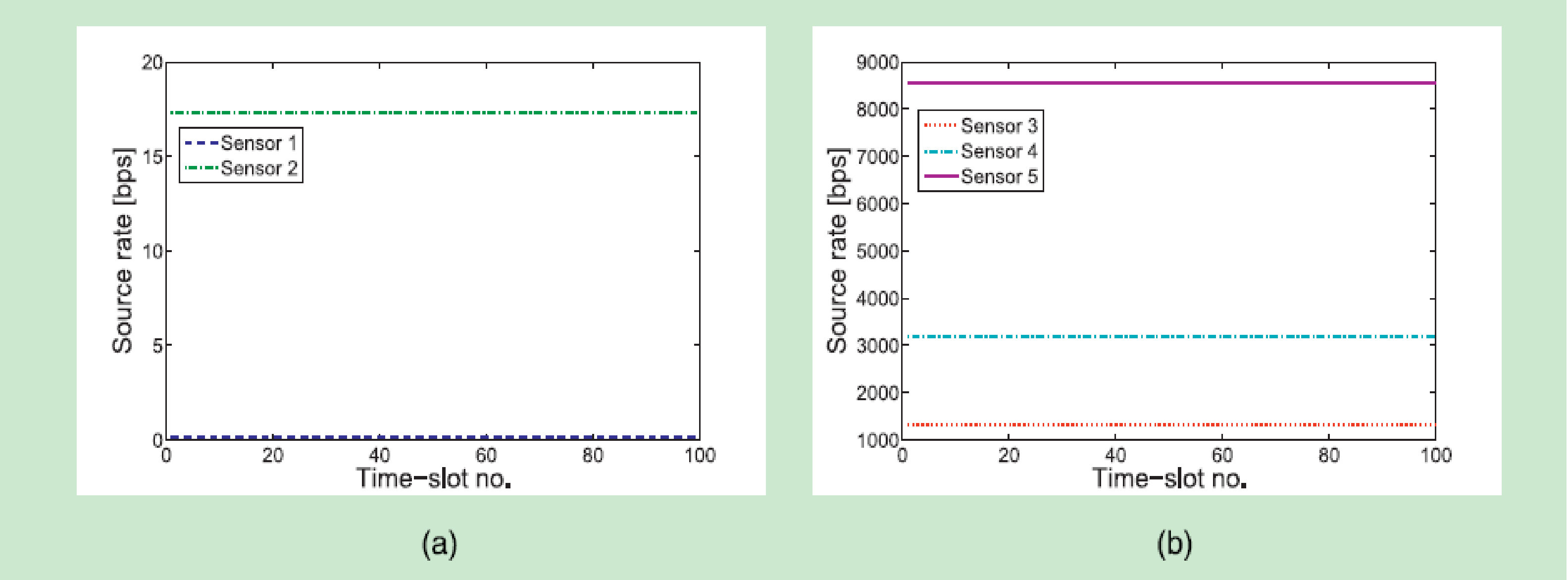
Protocol Implementation

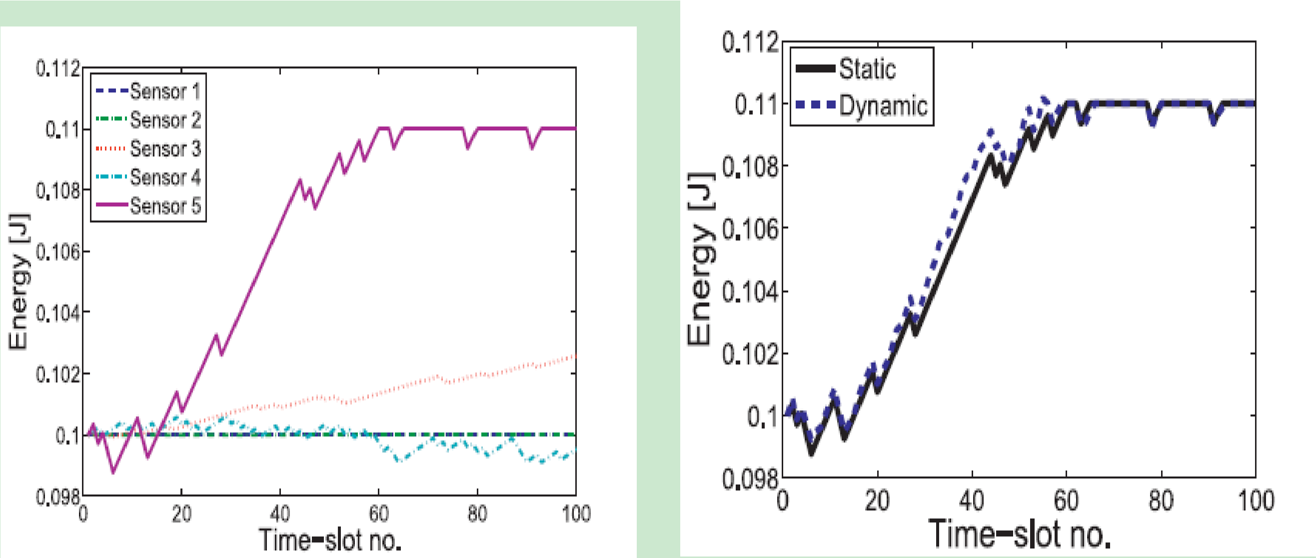
- Base station performs QoS optimization at each time slot.



Simulation

- Typical sensors:
- 1. body temperature sensor;
- 2. pulse oxygen sensor;
- 3. blood pressure sensor;
- 4. ECG sensor, and
- 5. electroencephalography (EEG) sensor.



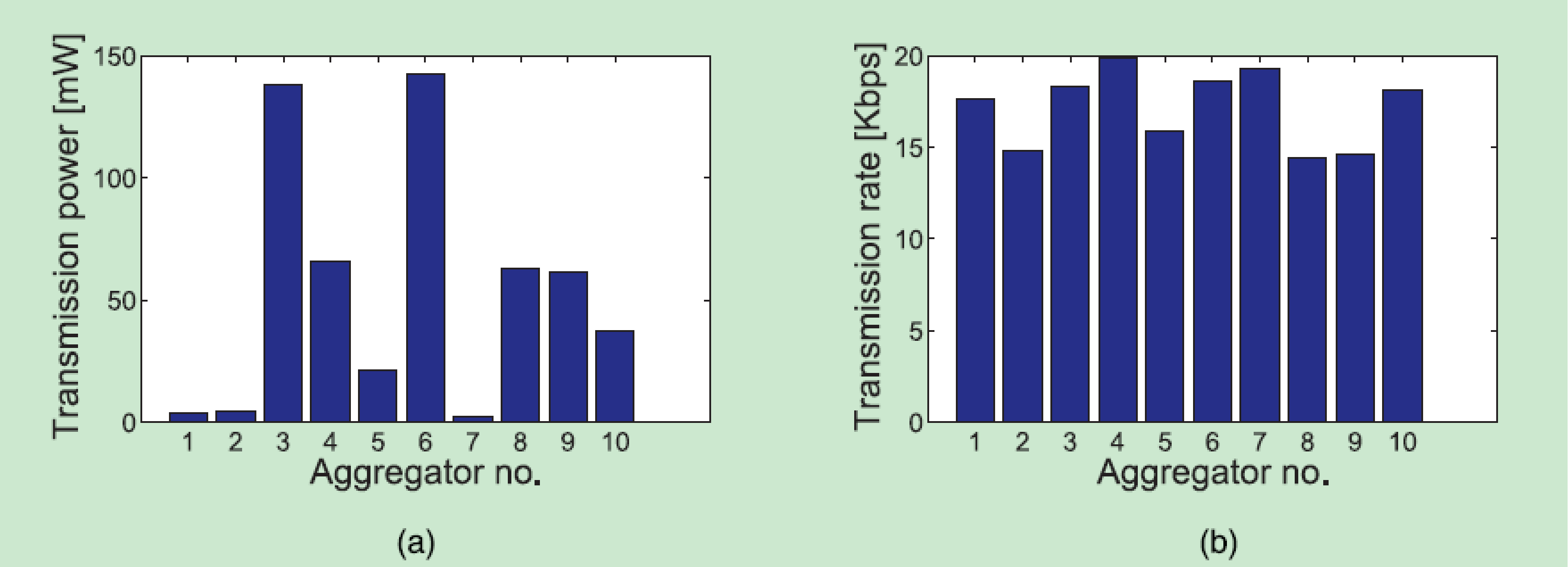


(a) (b)

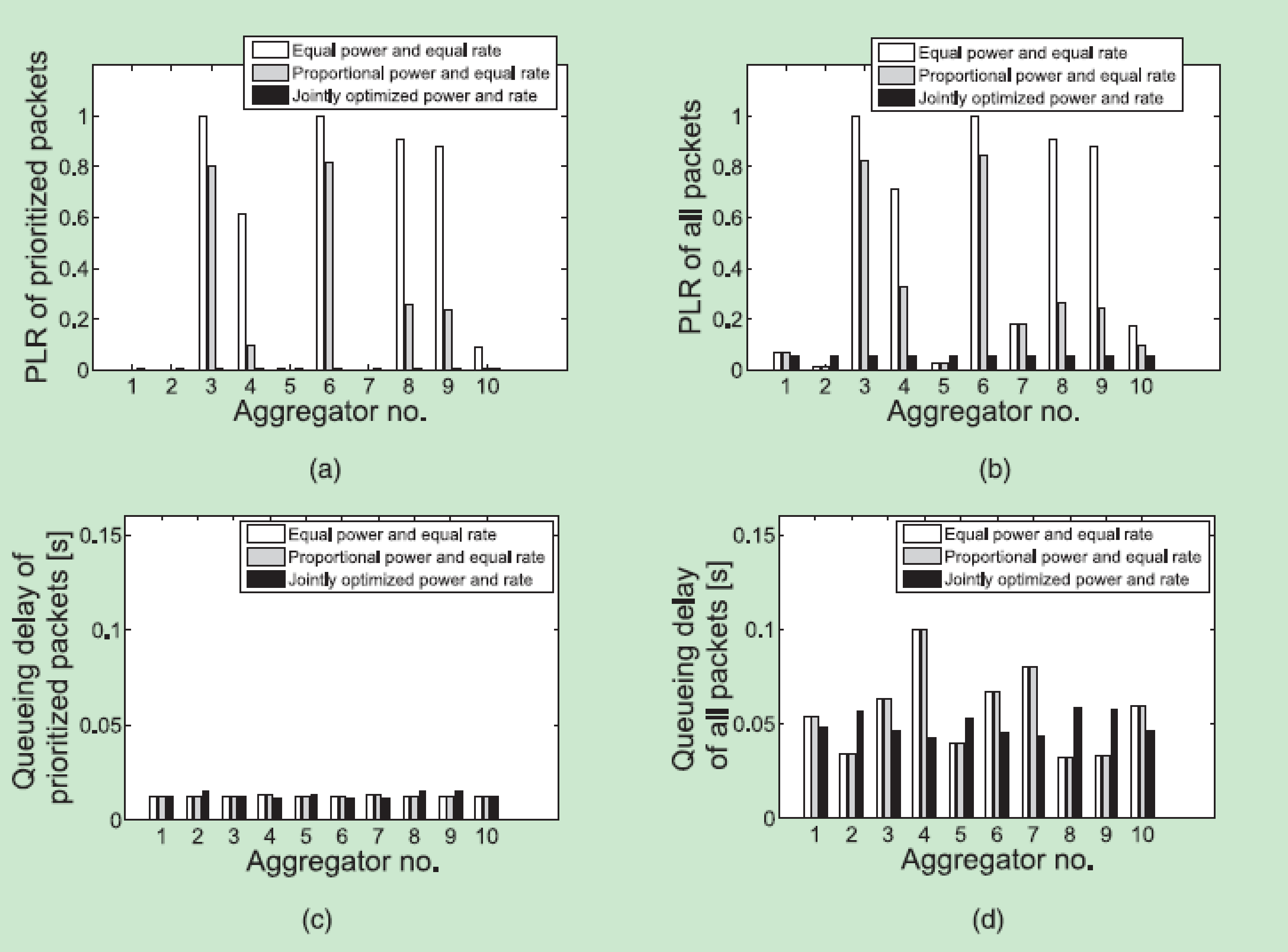
Fig. 6. Energy variations during 100 time slots: (a) at sensors 1-5 in a static state and (b) at sensor 5 in a static state and a dynamic state, respectively.

TABLE 2
Relationship between the Source Rate and the Lifetime of Sensor 3

Source rate [bps]	847	969	1090	1211	1332	1453	1574	1695
Minimum uninterrupted lifetime [s]	∞	∞	13228	6614	4409	3307	2646	2205
Maximum uninterrupted lifetime [s]	∞	∞	∞	∞	∞	∞	13228	6614



- Figure7: Optimal results obtained from the optimized scheme in an eHealth location with 10 subscribers: (a) transmission powers and (b) transmission rates.



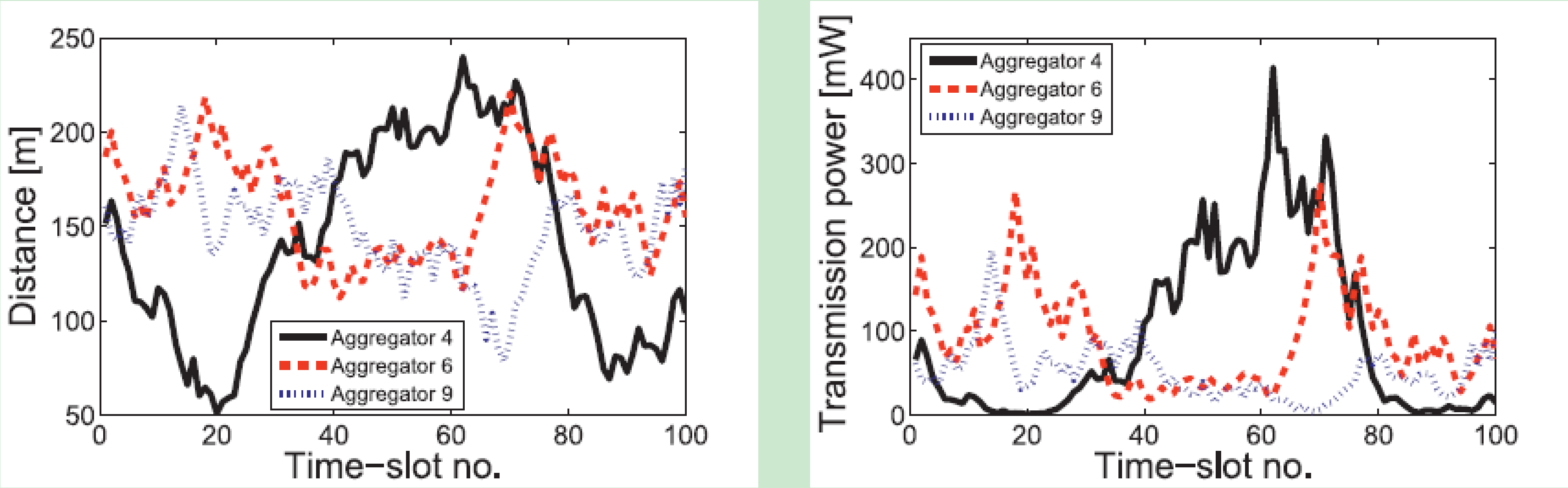
(a)

(b)

(c)

(d)

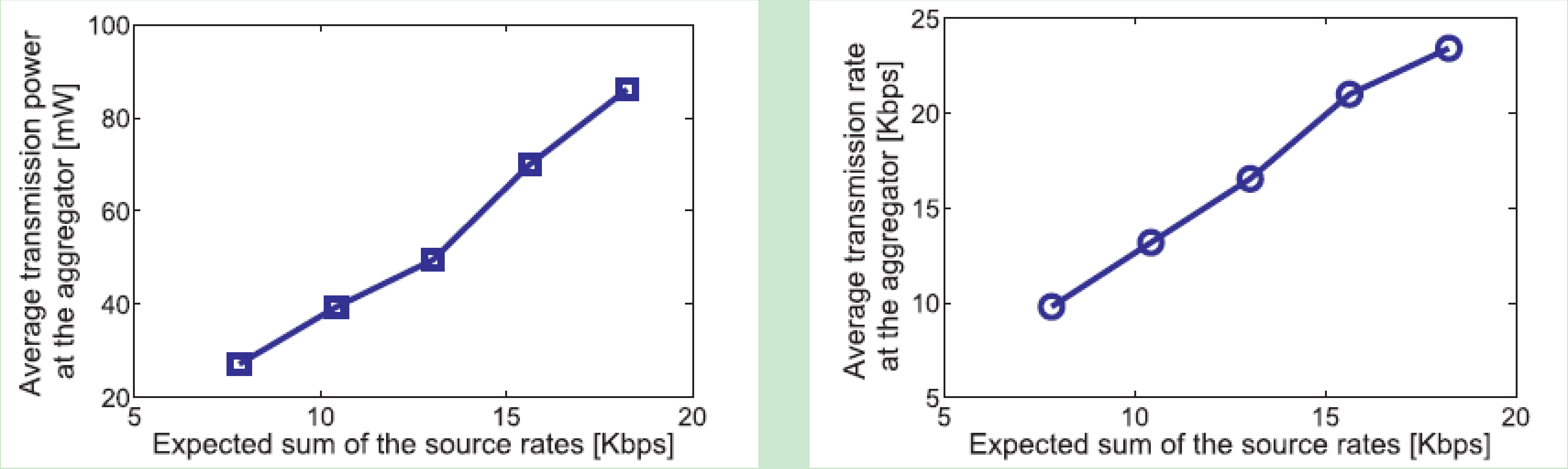
- Figure.8.Comparison of QoS metrics in an eHealth location with 10 subscribers: (a) PLR of prioritized packets, (b) PLR of all packets, (c) queuing delay of prioritized packets, and (d) queuing delay of all packets.



(a)

(b)

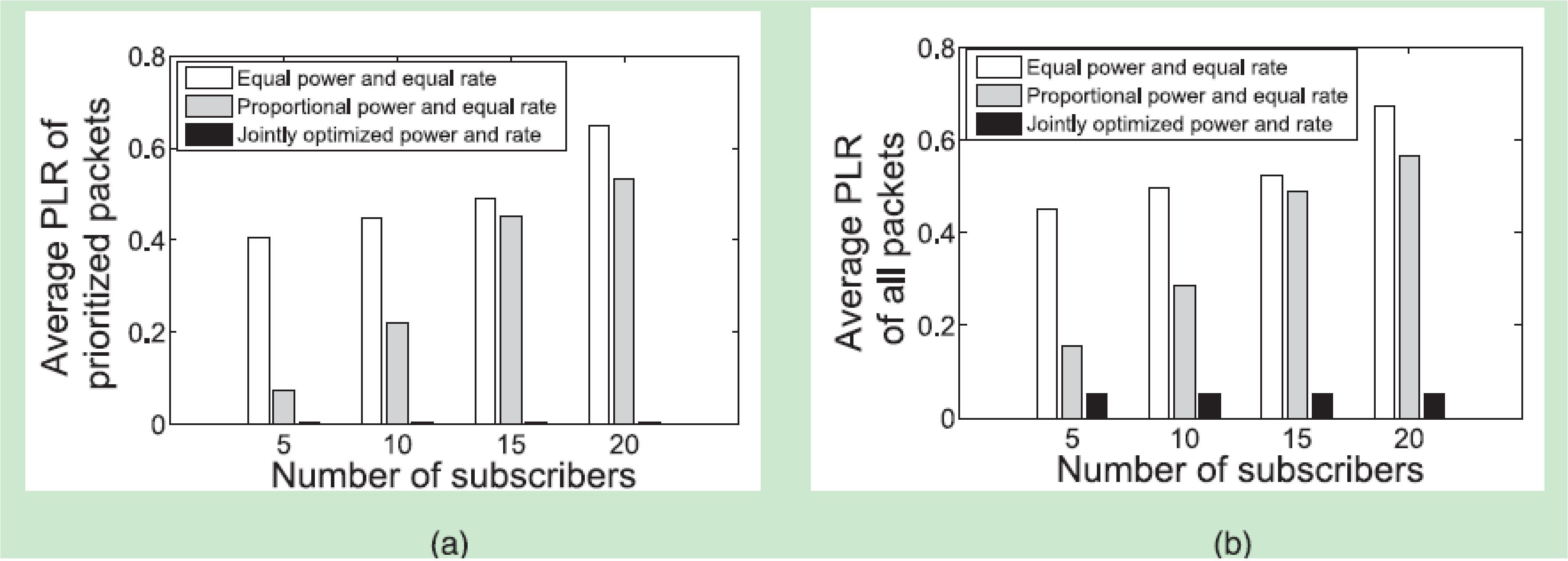
- Fig.9. Variation of transmission power due to the variation of the distance from the aggregator to the base station: (a) variation of the distance and (b) variation of the transmission power



(a)

(b)

- Figure.10. Relationship between the source rate of the sensors in a BSN and the transmission power and the transmission rate at the aggregator: (a) average transmission power and (b) average transmission rate



- Figure.11. Comparison of PLR with different number of subscribers in an eHealth location: (a) average PLR of prioritized packets and (b) average PLR of all packets

Conclusion

- Optimize the resource allocation to provide a sustainable and high-quality service in health monitoring systems.
- 1. steady-rate optimization → source rate
- 2. QoS optimization (jointly optimize)→ transmission power and transmission rate
- System Performance in terms of sustainability and service quality improves.