On-Chip Hybrid Power Supply System for Wireless Sensor Nodes

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Outline

- Background
- Research Proposal
- Research Contents
- Summary
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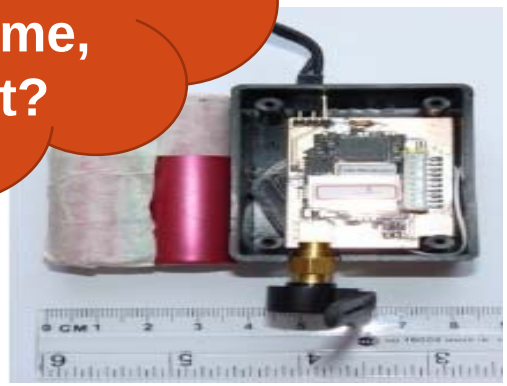
Background

- Wireless Sensor N

**Low power,
Small size,
Long lifetime,
Low cost?**



GPS Location

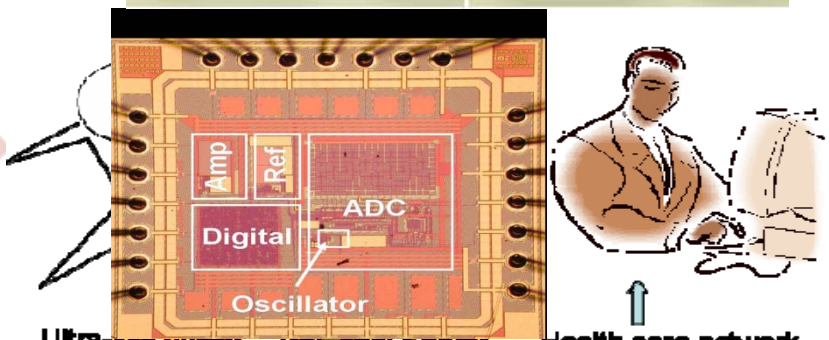
- 4cm~~5cm
- Long size !! [27]

Environmental Monitoring

- 100 days by battery rated at 860uAhr
- Short lifetime[28]

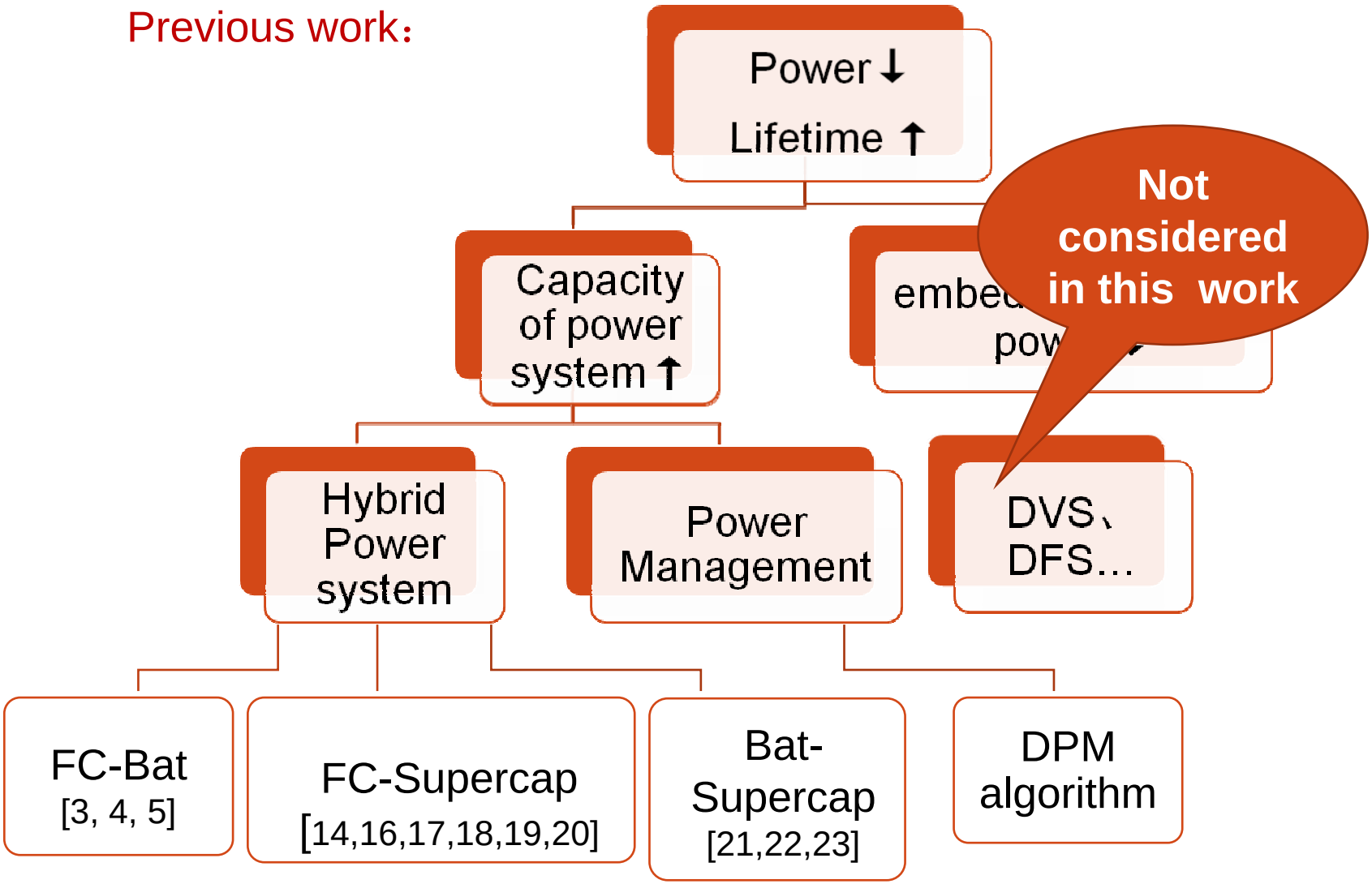
Biomedicine

- Area: 1000*700um [29]



Background

Previous work:



Background

1.High energy density
2.Environmental friendly
3.Slow load current following ability!!

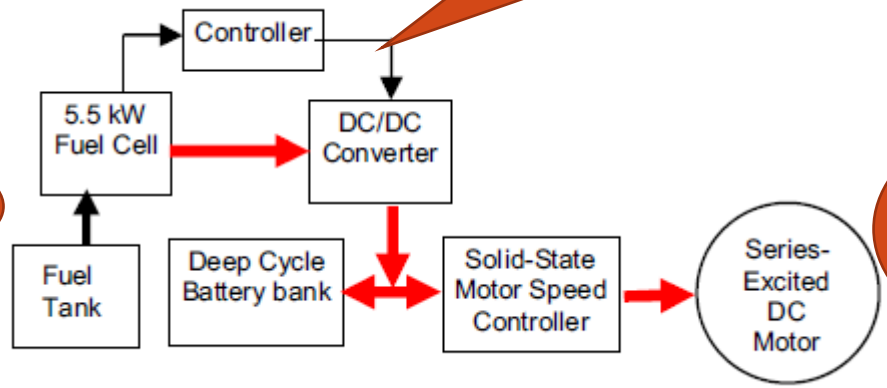
- Comparison of Single Power Systems[30]

Char.	Supercap	Cap	FC	Bat
Discharging time	[10^{-3},1]s	[10^{-9} ,1]ms	[10,300]hr	[1,10]hr
Lifetime	>30k hr	>100k cycles	1.5-10 khr	150-1500 cycles
Weight	1-2g	1g-10kg	20g-5kg	1g-10kg
Power density	[10, 100] kW/kg	[0.25, 10000] kW/kg	[0.001, 0.1] kW/kg	[0.005, 0.4] kW/kg
Energy density	[1, 5] Wh/kg	[0.01, 0.05] Wh/kg	[300, 3000] Wh/kg	[8, 600] Wh/kg
Max. Output current	100A	1000A	150mA/cm2	5A

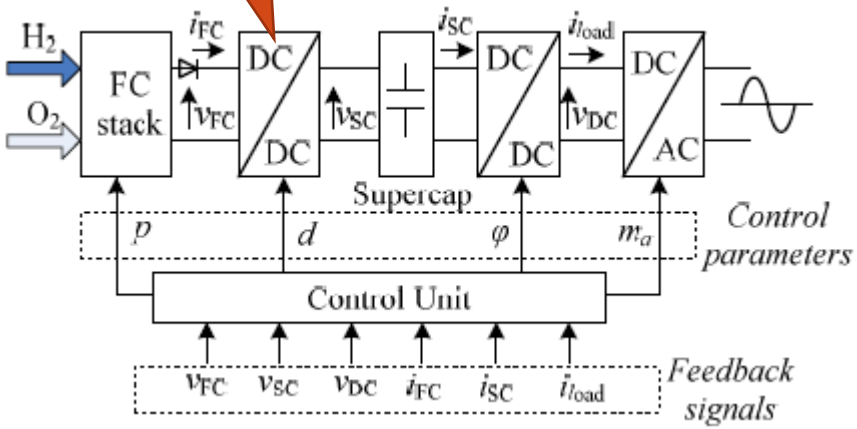
Background

Hybrid Power Systems:

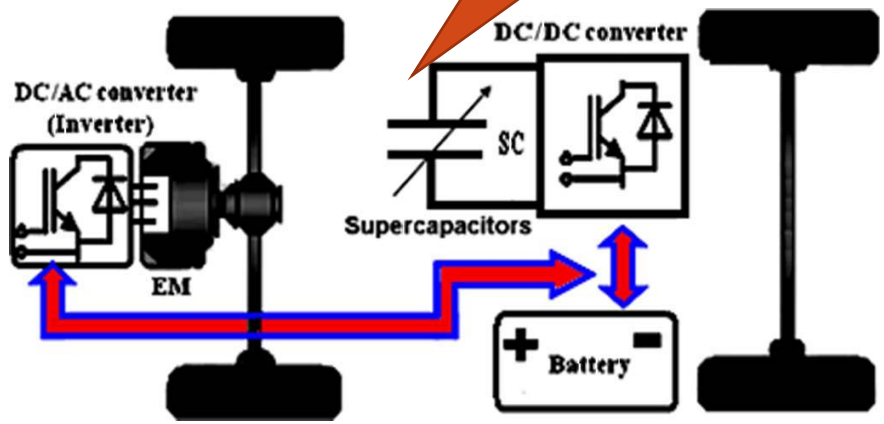
FC-bat Application



FC-Supercap Application



Battery-Supercap application



Backg

The best choice for WSN

- High energy density
- Good load current following ability
- Applied in Mobile devices

FC-Bat Hybrid Power System [3, 4, 5]

- High energy density
- Large peak current provided
- No well short step current provided
- Applied in motors

FC-Supercap Hybrid Power System [14,16,17,18,19,20]

- Low energy density
- Well frequency characteristic
- Applied in high-power applications

Bat-Supercap Hybrid Power System [21,22,23]

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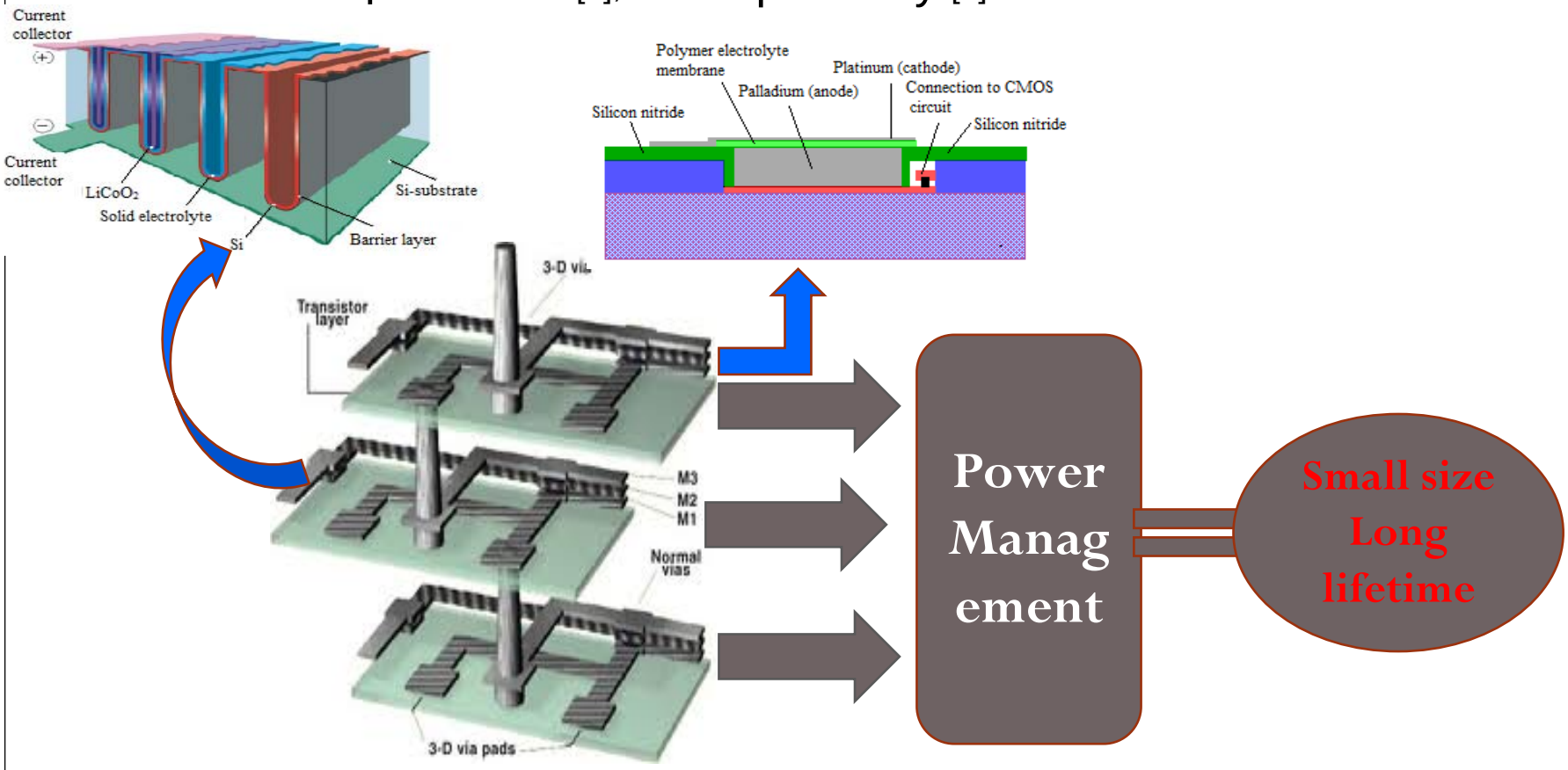
Research Proposal

- On chip fuel cell [2], on chip battery [6] and DPM included.



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  - DPM algorithm
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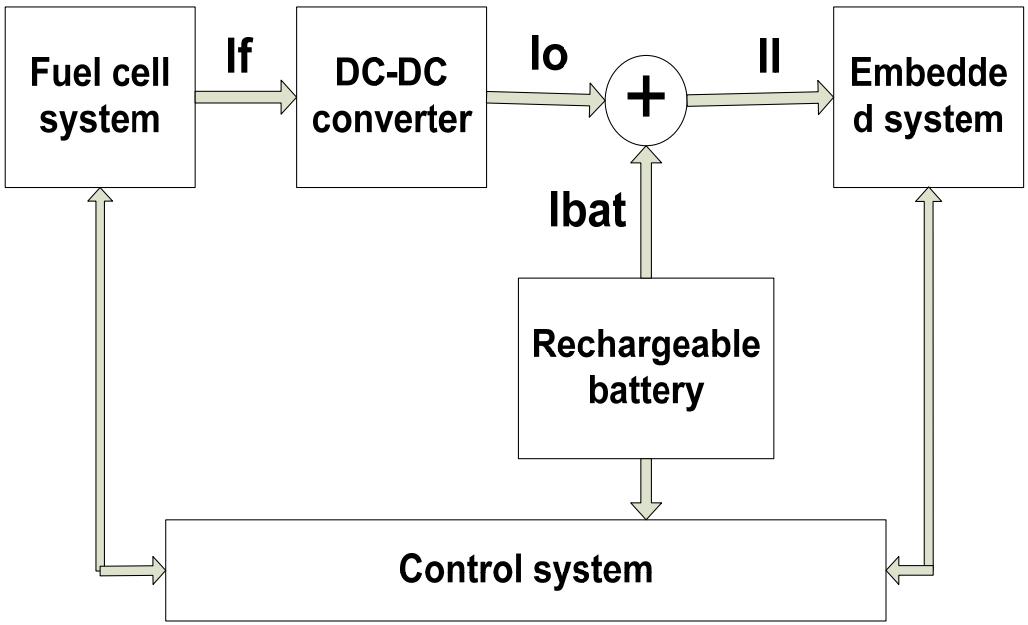
System architecture



Working Principle：

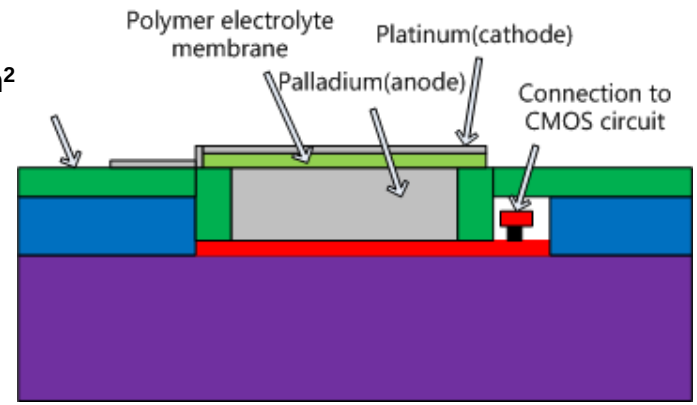
Suppose working at a constant voltage, when load current Il<Io, Then extra current, Io-Il will be used to charge the rechargeable batteries.

when load current Il>Io, then the rechargeable batteries will provide the extra current Il-Io.

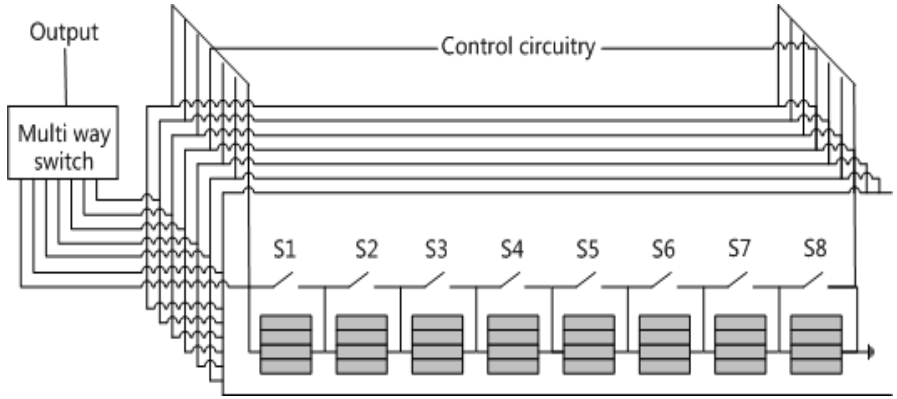
System architecture

- On chip Fuel cell[2]

Energy density：500mAh/cm²

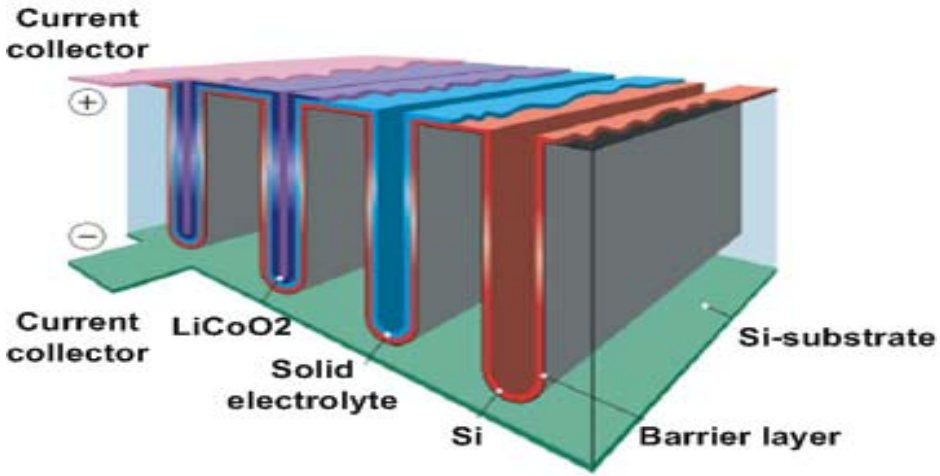


FCCs



- 3D on chip rechargeable battery(*in Peter H.L. etc* [6])

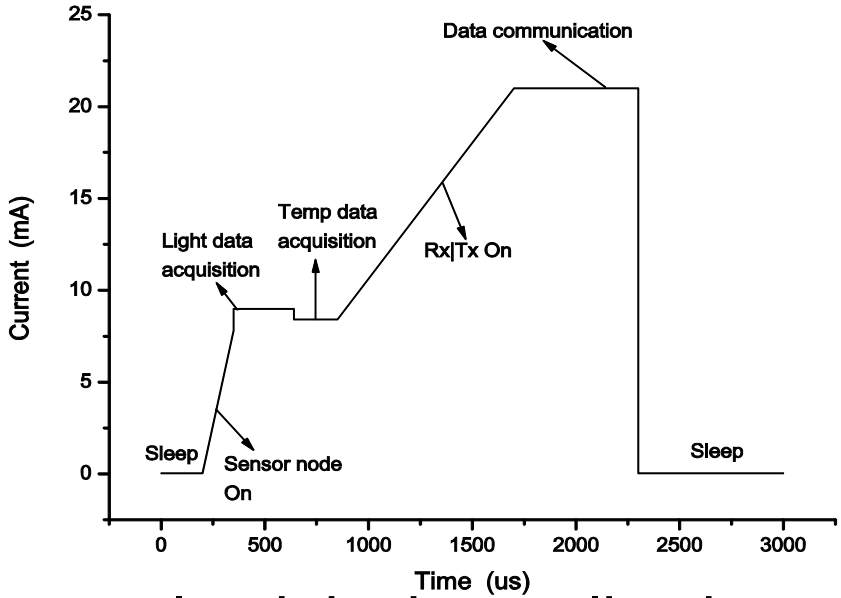
Energy density：5mWh/um*cm² 3 order larger than present on chip capacity



System architecture

- The load and control unit

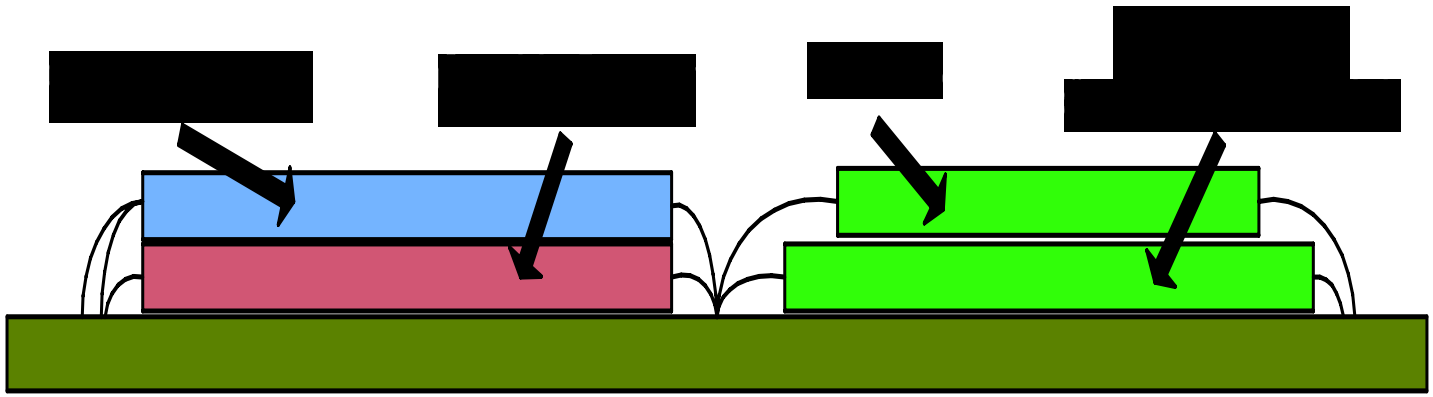
（1） Wireless sensor node is used as the load



（2） The control unit is the realization of DPM algorithm

System architecture

- 3D architecture



This system is consisted of on chip power system and wireless sensor node. Wire bonding is used as the interconnection method.

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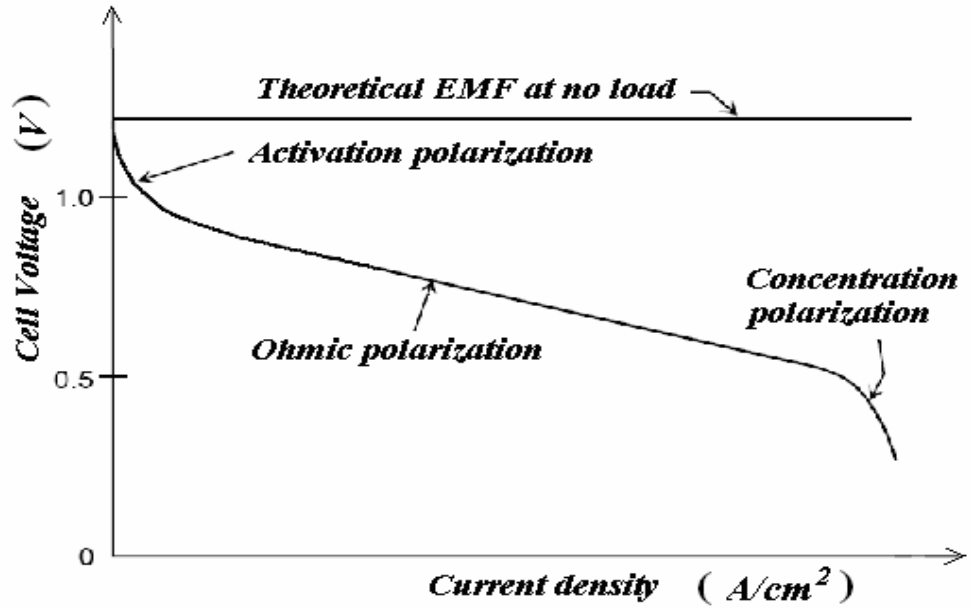
Mathematical modeling

Fuel cells:

According to the I-V characteristic of fuel cells, it is divided into three regions：

(a) Activation polarization, (b) Ohmic polarization,

(c) Concentration polarization [7].



Mathematical modeling

- Each region can be modeling by an expression.

Activation polarization	$V_A = A \ln(\frac{I}{I_o})$
Ohmic polarization	$V_R = RI$
Concentration polarization	$V_c = mI_m e^{nI_n}$

Mathematical modeling

- Rechargeable batteries:

According to the real charging and discharging characteristic of batteries[6]，two segments can be used to model the charging/discharging characteristics：

$$V = \begin{cases} 0.5 * SOC + 0.8 & 0 < \mathrm{SOC} < 0.2 \\ 0.25 * SOC + 0.85 & 0.2 < \mathrm{SOC} < 1 \end{cases}$$

And，SOC is the State of Charge of the batteries.

$$SOC = (\int_0^t (I_o - I_l) dt) / C_{\max}$$

Mathematical modeling

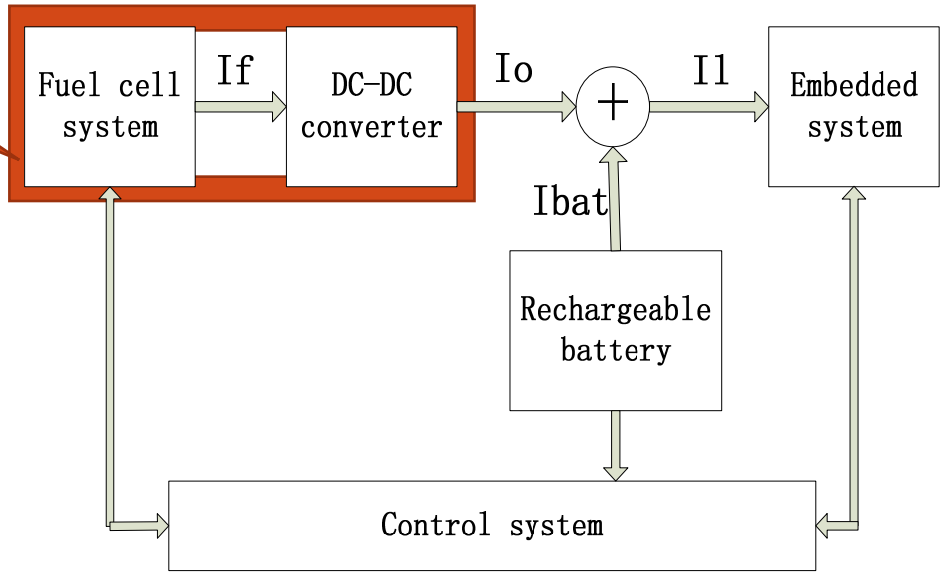
- Converting efficiency of FC and DC-DC system

One linear model is used to define the converting efficiency [4]

$$\eta_s = \alpha - \beta I_o$$

d α, β are decided by the actual converting efficiency.

Linear converting efficiency



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DPM algorithm

Goal：For one task, looking for the optimal output current of FCCs, which leads to the minimal fuel consumption.

Optimal object：**Fuel consumption within one cycle equals to fuel consumption of Idle state pluses that of Active state.**

$$\text{Minimize}: \quad C_{fc}(k) = \mathrm{I}_{fc/I}(k) * T_I(k) + I_{fc/A}(k) * T_A(k) \tag{1}$$

The converting efficiency

$$\eta = (\mathrm{V_o} * \mathrm{I_o}) / \Delta_{\mathrm{Gibbs}} \approx (\mathrm{V_o} * \mathrm{I_o}) / (\zeta * \mathrm{I_{fc}})$$

Then,

$$\approx \alpha - \beta \mathrm{I_o} \tag{2}$$

$$I_{fc} = (V_o * I_o) / (\zeta * (\alpha - \beta \mathrm{I_o}))$$

Formula（1）can be revised as

$$\text{Minimize}: \quad C_{fc}(k) = (V_o * I_{o/I}(k)) / (\zeta * (\alpha - \beta \mathrm{I_o}(\mathrm{k}))) * T_I(k) \tag{3}$$

$$+ (V_o * I_o(k)) / (\zeta * (\alpha - \beta \mathrm{I_o}(\mathrm{k}))) * T_A(k)$$

DPM algorithm

Constraints:

(1)Limit capacity of rechargeable battery:

$$Q_{ini}(k) + (I_{o/I}(k) - I_{l/I}(k)) * T_I(k) \leqslant C_{\max}$$

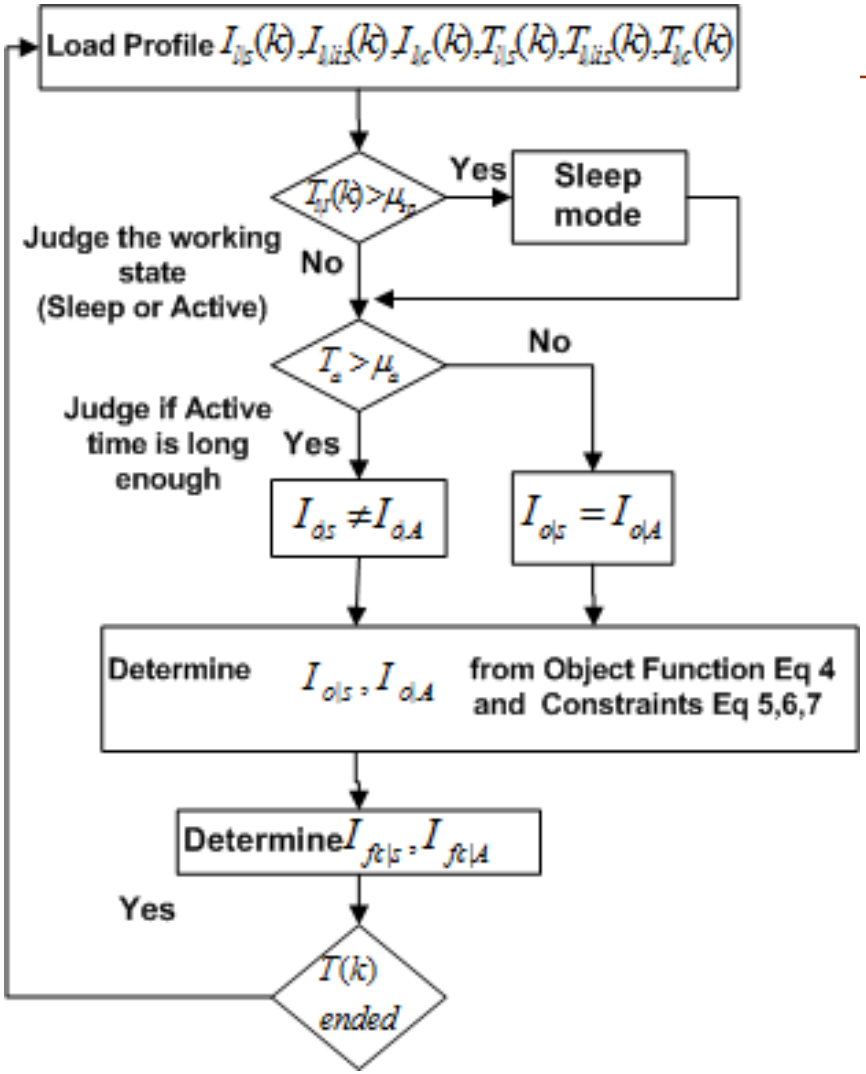
(2)FC Load following ability：

$$I_o \in [0.01, 1]$$

(3)Conversation of charge in rechargeable battery：

$$Q_{ini}(k) + (I_{o/I}(k) - I_{l/I}(k)) * T_I(k) = (I_{l/A}(k) - I_{o/A}(k)) * T_A(k) + Q_{end}(k)$$

DPM algorithm



Load Profile
(current and states' time**)**

Working state judgement

Optimization

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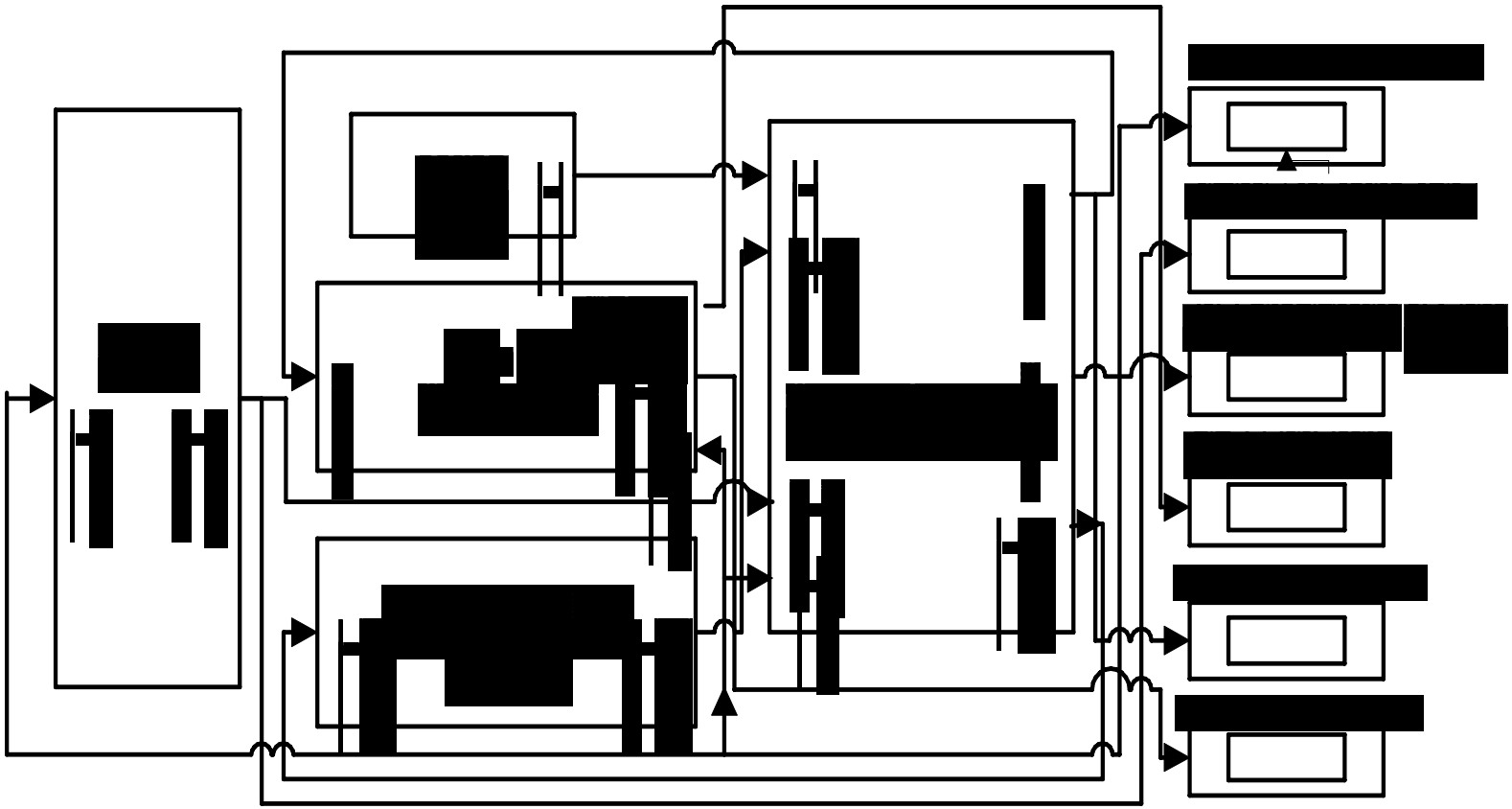
Simulation

- simulation platform in Matlab/simulink



Simulation

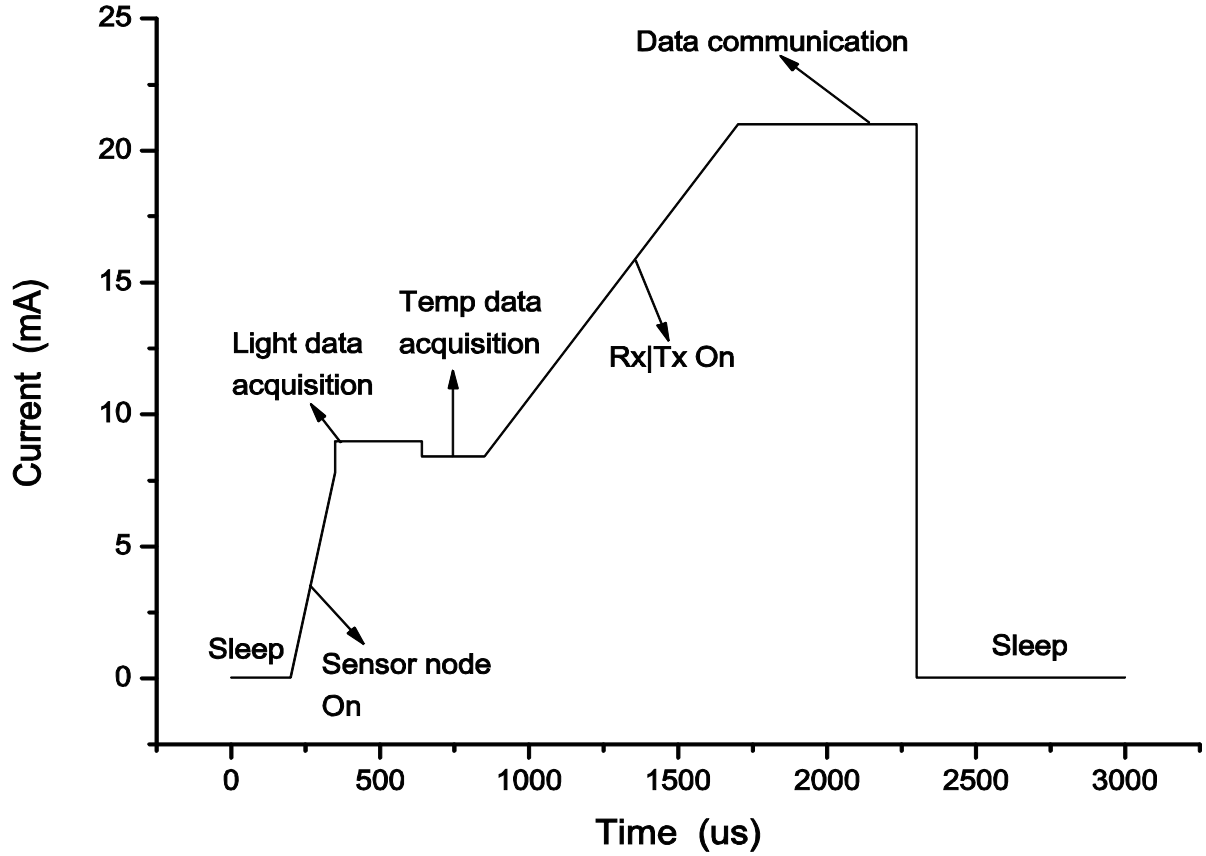
- some basic model parameters

Capacity of FCCs	Capacity of rechargeable batteries	Chip area	Thickness of the chip	FCCs open voltage	Output current region of FCCs
500 mAh	2 .0 mWh	1 .0 cm^2	50 um	3.0 V	0.02mA ~ 1.0mA

Simulation

- Simulation results analysis——*the sensor node*

（referring to *Berkeley's Great Duck Island Program*）



Simulation

- Simulation results analysis——*comparison with traditional battery*

Power system	Chip area (cm^2)	Capacity (mAh)	Energy consumption per cycle(mJ)	Lifetime (year)
Battery（wafer-level）[27]	1	45*2	1.9208	0.374
FC-Bat		500	1.6140	2.475

Simulation

- Simulation results analysis——*fi*
  states of sensor nodes

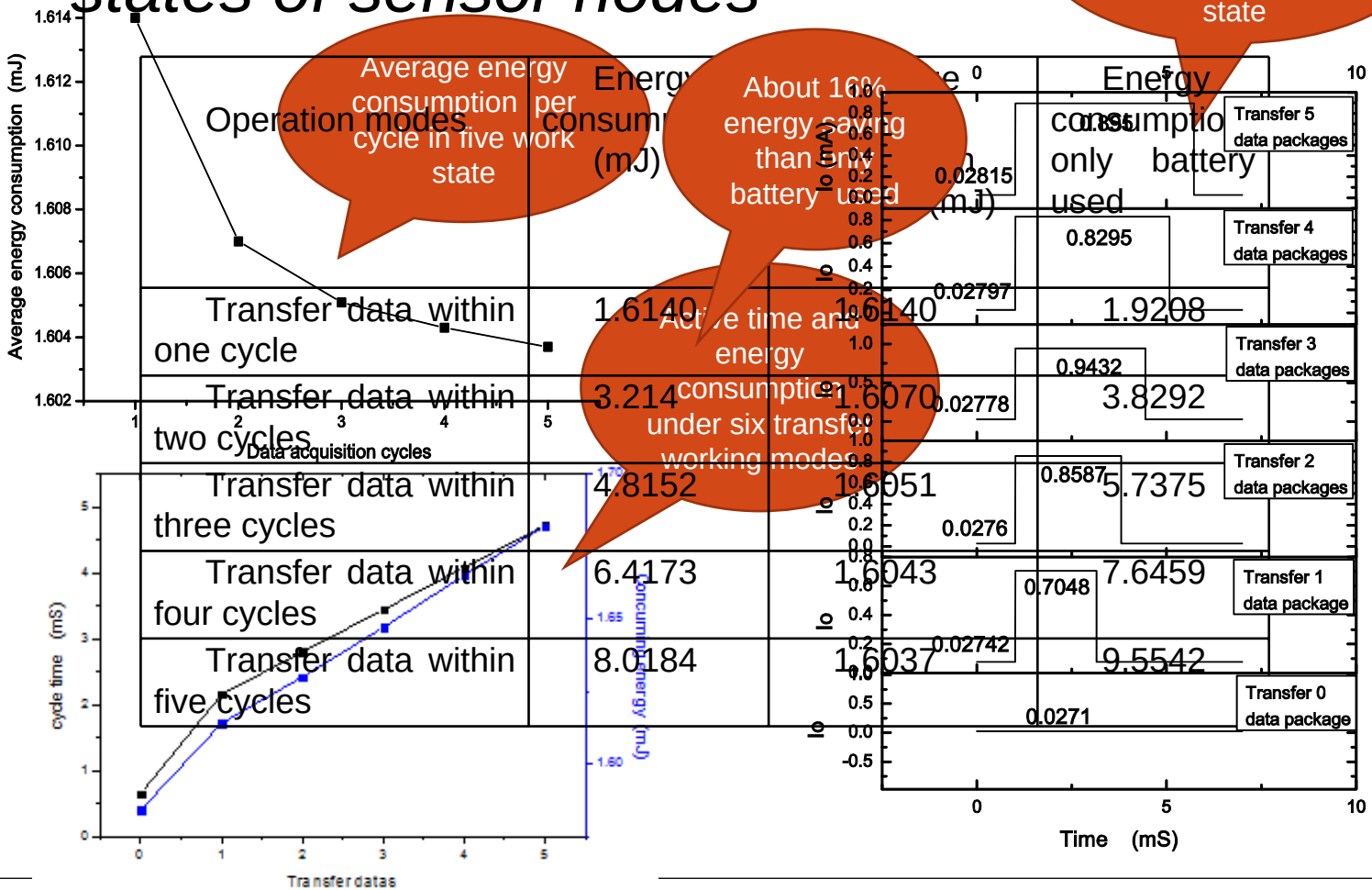
Output current of Fuel cells within one transferring cycle in six work state

Average energy consumption per cycle in five work state

About 16% energy saving than only battery used

Active time and energy consumption under six transfer working modes

Operation modes	Energy consumption (mJ)		Energy consumption only battery used (mJ)
Transfer data within one cycle	1.6140	1.6140	1.9208
Transfer data within two cycles	3.214	1.6070	3.8292
Transfer data within three cycles	4.8152	1.6051	5.7375
Transfer data within four cycles	6.4173	1.6043	7.6459
Transfer data within five cycles	8.0184	1.6037	9.5542



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Summary

- Proposed one on chip fuel cell based hybrid power system
- Proposed the 3D architecture of this on chip fuel cell based hybrid power system
- Proposed a DPM algorithm of fuel cell based hybrid power system for wireless sensor node.
- Build the simulation platform in Matlab/ simulink

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Thanks!& Best wishes!

Q&A？