Optimal Resource Allocation for Wireless Video Sensors

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Outline

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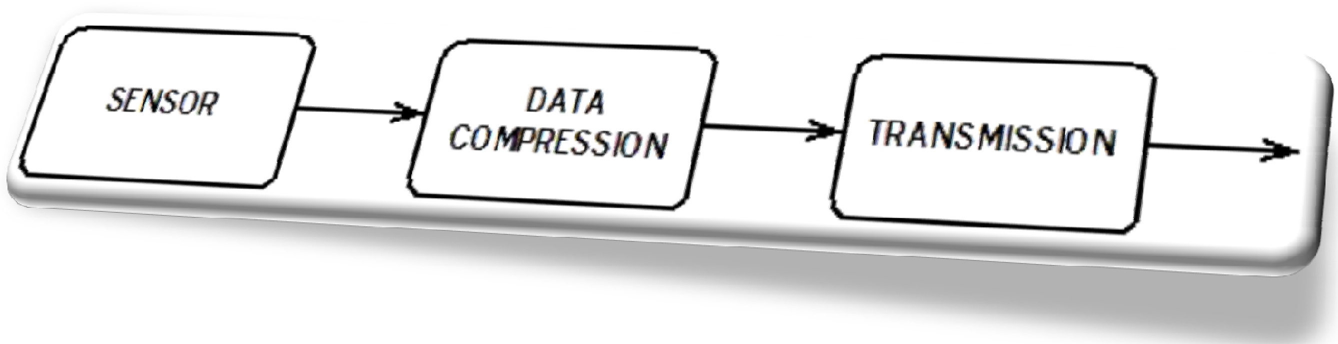
II	• Optimal Power Allocation
III	• P-R-D Analysis for ΣΔ Imager
IV	• Power Control
V	• Conclusion

Optimal Allocation in Classical Video Communication Systems

- System optimization problem: how to control system performance under bandwidth constraints.
- *Rate-distortion (R-D)* characteristics provide the minimum number of bits that has to be transmitted to achieve a given level of distortion.
- Examples: digital TV broadcast, video on demand [1],[2].

Wireless Video Sensor Networks

- A wireless video sensor network is a system that contains spatially distributed *wireless video sensors (WVSs)*.
- Three major modules of the WVS are image sensing, video compression, and wireless transmission.



Optimal Allocation in Wireless Video Sensor Network

- Wireless video sensor networks operate under limited energy supply. The available energy influence the resulting video quality and the life time of the system.
- For optimal resource allocation, classical R-D analysis has to be extended to include additional resource constraints.
- A new, *power-rate-distortion (P-R-D)* analysis has to be applied for power and bit allocation [1],[2].

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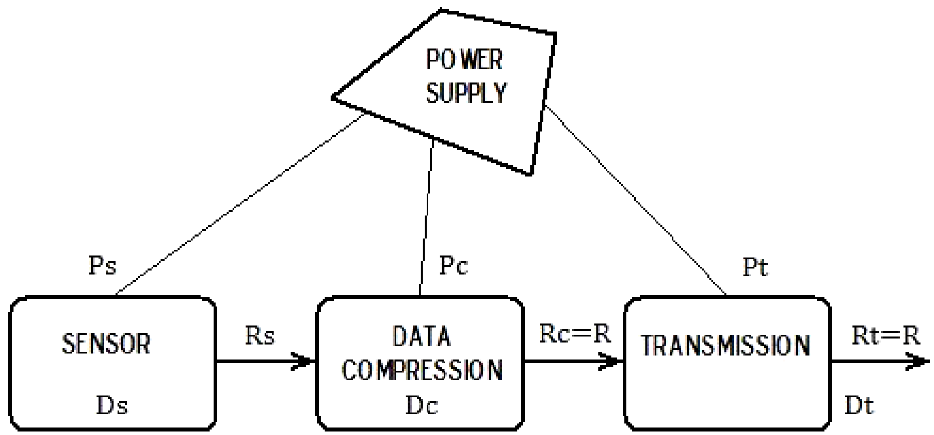
Optimization Problem



- How to allocate power P among sensor (Ps), compression (Pc), and transmission (Pt) modules to minimize the overall distortion for a given rate R?
- In addition, output bit rate of the sensor should be higher than target bit rate but should not excide maximum achievable rate.

Optimization Problem (Cont.)

•Distortion in the module: the mean square error difference between the output and input pictures of the module.

•Distortions introduced by the three modules can be assumed to be independent so that overall distortion is simply the sum of all three.

$$\min_{P_s, P_c, P_t} D(P_s, P_c, P_t; R) = D_s(P_s) + D_c(P_c; R) + D_t(P_t)$$

$$s.t. P_s + P_c + P_t = P$$

$$R \leq R_s(P_s) \leq R_{s\max}$$

Optimal Solution I

- Assume that solution lies in the region

$$R \le R_s(P_s) \le R_{s\max}$$

- We can use Lagrange multiplier technique:

$$\Lambda(P_s, P_c, P_t, \lambda; R) = D_s(P_s) + D_c(P_c; R) + D_t(P_t) + \lambda(P_s + P_c + P_t - P)$$

Optimal Solution I

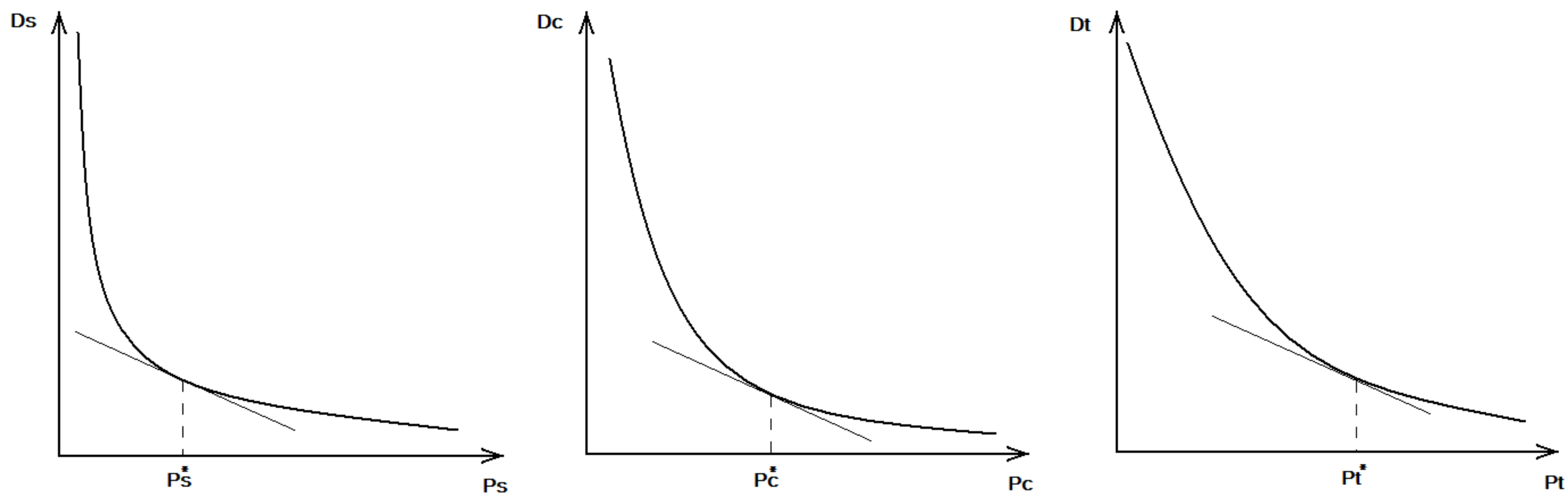
$$\left.\begin{aligned}\frac{\partial D_s}{\partial P_s}+\lambda=0\\ \frac{\partial D_c}{\partial P_c}+\lambda=0\\ \frac{\partial D_t}{\partial P_t}+\lambda=0\end{aligned}\right\}\Rightarrow \frac{\partial D_s}{\partial P_s}=\frac{\partial D_c}{\partial P_c}=\frac{\partial D_t}{\partial P_t}$$

$$P_s+P_c+P_t=P$$

•All functions Di (Pi) are convex function —> the solution is the global minimum.

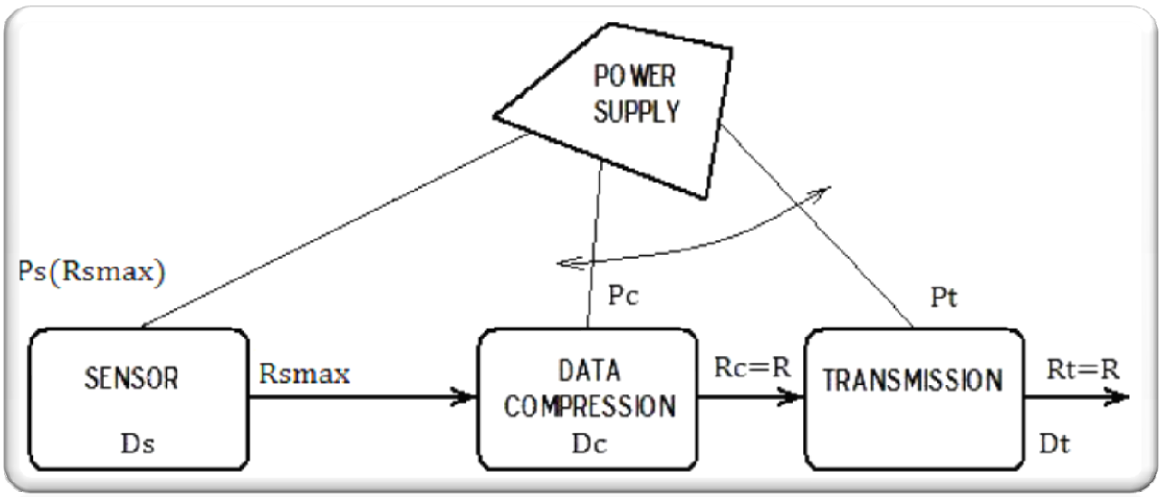
Graphical interpretation

- For an optimal solution P_s^*, P_c^*, P_t^*, the tangents on the corresponding distortion functions must have the same slope.



Optimal Solution II

- If Rs>Rsmax then Rs=Rsmax should be set.

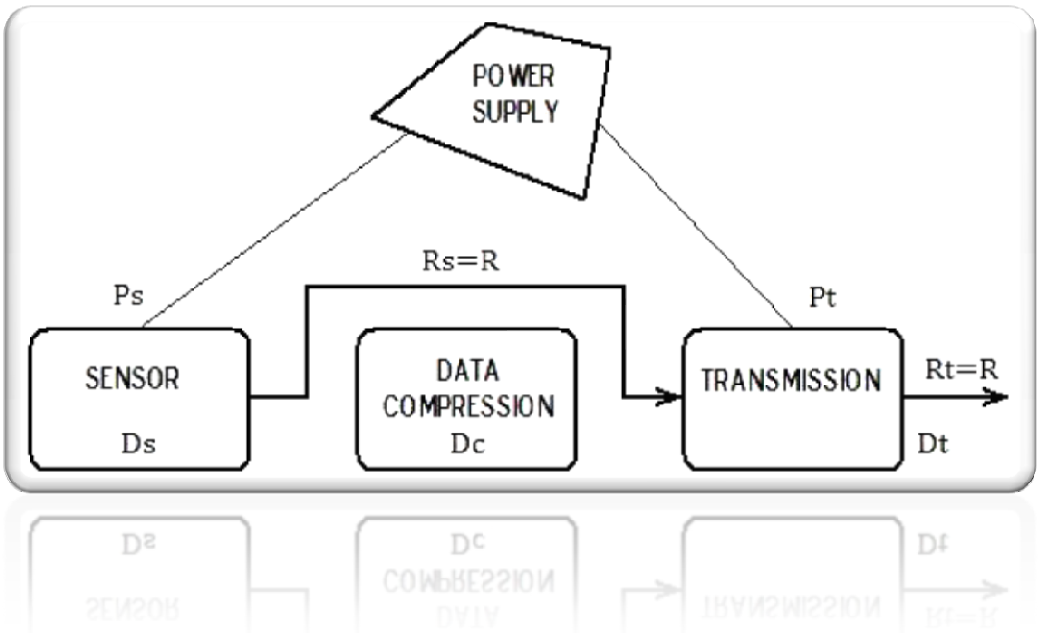


$$\frac{\partial D_c}{\partial P_c} = \frac{\partial D_t}{\partial P_t}$$

$$P_c + P_t = P - P_s\left(R_{s\max}\right)$$

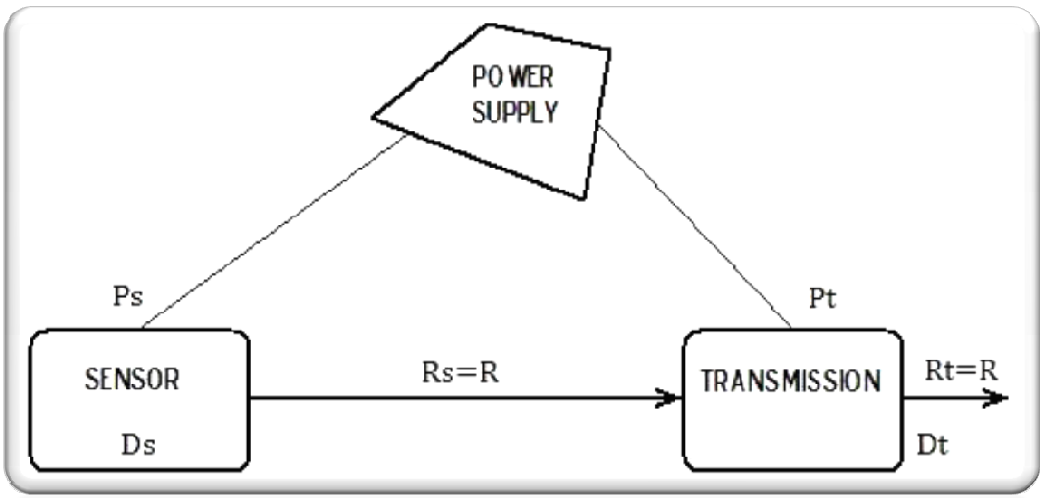
Optimal Solution III

- If Rs<R then Rs=R should be set.



$$P_s = P_s(R)$$
$$P_c = 0$$
$$P_t = P - P_s$$

New optimization problem



$$\frac{\partial D_s}{\partial P_s} = \frac{\partial D_t}{\partial P_t}$$

$$P_s + P_t = P$$

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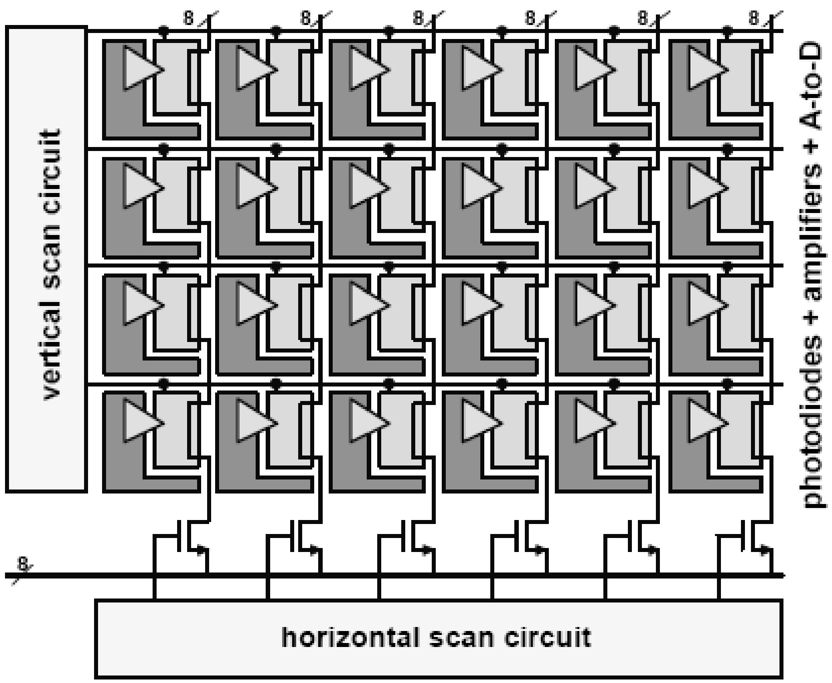
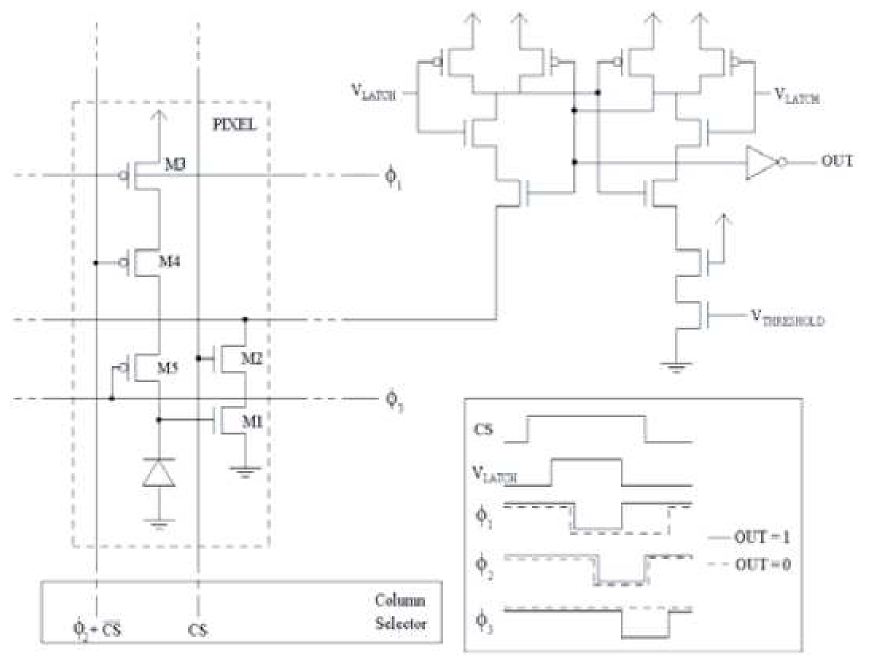
Architecture of ∑Δ Imager

Digital Pixel Sensor Architecture



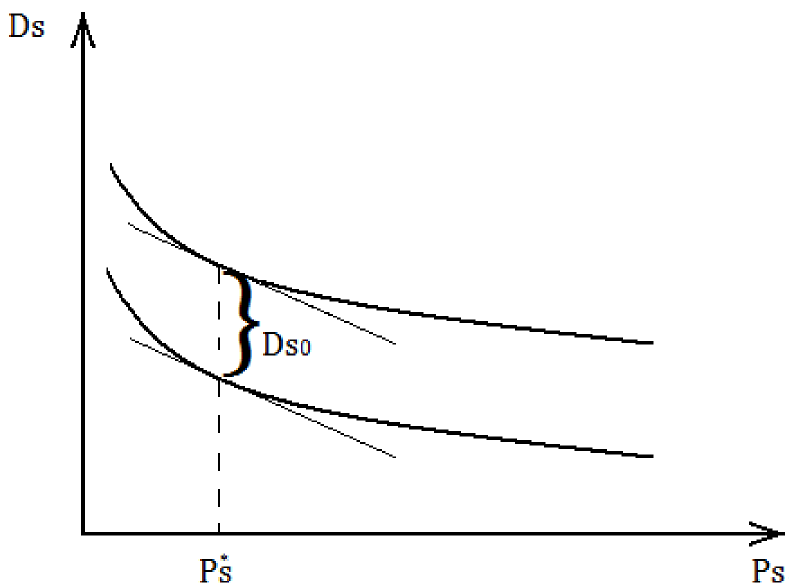
Pixel Design



*A. Theuwissen, "CMOS Image sensors: Recent Developments"

*Z.Ignjatovic and M.Bocko, "A 0.88nW/pixel, 99.6dB linear-dynamic-range fully-digital image sensor employing a pixel-level sigma-delta ADC," VLSI Simposium, 2006.

Distortion model for ∑Δ Imager



$$D_s^{'} = D_s + D_{s0}$$

$$\frac{\partial D_s^{'}}{\partial P_s} = \frac{\partial D_s}{\partial P_s}$$

- Distortions: quantization noise and thermal reset noise
- Optimal solutions depend on the rate of change of the distortion function with respect to power (OSR).
- Any model that include non-idealities like photodiode shot noise, 1/f noise, FPN, DC offset etc. (which do not depend on the OSR) will lead to the same power allocation as the proposed model in the region R≤Rs ≤ Rsmax.

Quantization noise

- Assumptions about quantization noise e[n]:
  - -stationary random process
  - -random variables of the error process are uncorrelated – e[n] is white noise
  - -$e[n] \sim U(-\Delta/2, \Delta/2)$, Δ-quantization step
  - -e[n] is uncorrelated with input signal x[n]
  - -quantization noise power is $\sigma_q^2 = e[n]^2 = \Delta^2/12$

*P.M. Aziz, H.V. Sorensen, and J. vn der Spiegel, "An overview of sigma-delta converters," IEEE Signal Processing Magazine, vol. 13, No. 1, pp. 61-84, Januar 1996.

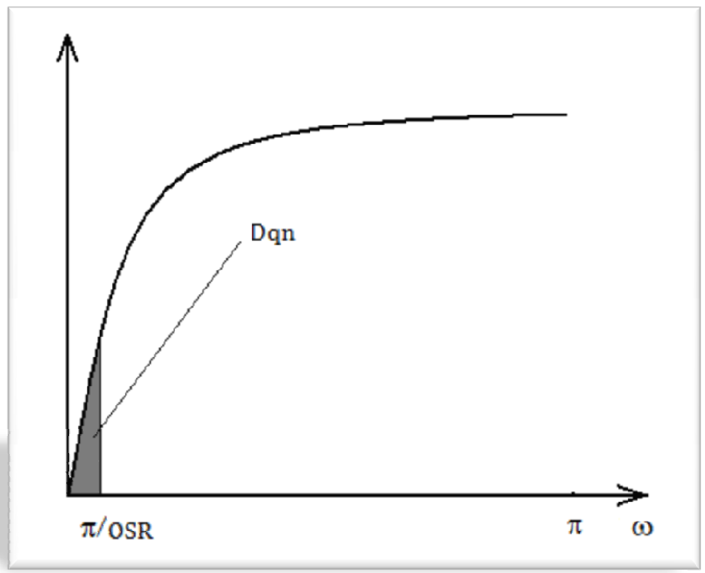
Quantization noise (Cont.)

•Distortion measure is in-band noise power.

$$D_{qn} = \int_{-\pi/OSR}^{\pi/OSR} \left|1 - e^{-jw}\right|^2 \frac{\sigma_q^2}{2\pi} dw$$

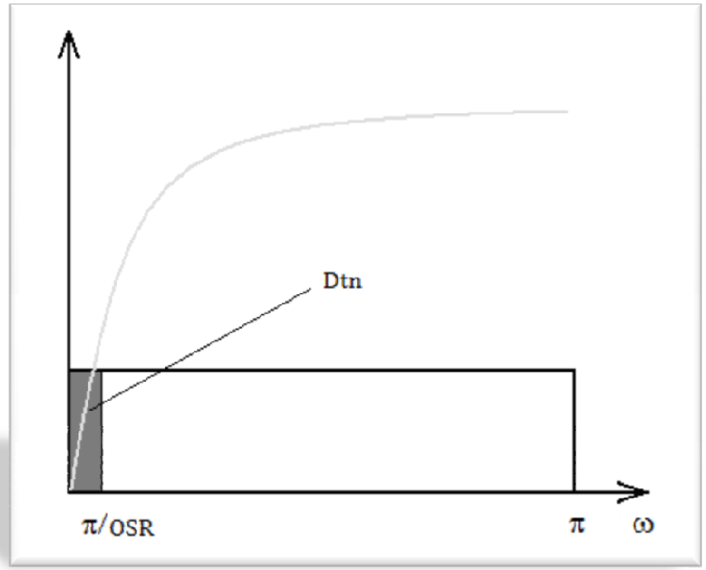
$$D_{qn} = \frac{2\sigma_q^2}{\pi}\left(\frac{\pi}{OSR} - \sin\frac{\pi}{OSR}\right)$$

$$D_{qn} \overset{OSR>>\pi}{\approx} \frac{\pi^2 \sigma_q^2}{3OSR^3}$$



Thermal (reset) noise

•Thermal noise is assumed to be a stationary white random process with Gaussian distribution with zero mean and variance σ_t^2.
•As opposed to the quantization noise, the thermal noise does not see the integration function and it is reduced only by oversampling.



$$D_{tn} = \int_{-\pi/OSR}^{\pi/OSR} \frac{\sigma_t^2}{2\pi} dw = \frac{\sigma_t^2}{OSR}$$

Total Distortion in ∑Δ Imager

•Noise sources are assumed to be independent; therefore, total distortion is sum of individual distortions:

$$D_s = D_{qn} + D_{tn}$$

$$D_s = \frac{2\sigma_q^2}{\pi}\left(\frac{\pi}{OSR} - \sin\frac{\pi}{OSR}\right) + \frac{\sigma_t^2}{OSR}$$

Power Consumption

$$P_s = N_{pixel} \cdot f_{frame} \cdot OSR \cdot P_{pf}$$

$$P_s = OSR \cdot p$$

- N_{pixel} -number of pixel in the image sensor array
- f_{frame} -number of frames per second in video frame sequence
- P_{pf} -power consumption per pixel per frame
- p -dynamic power consumption per oversampling

Power-Distortion Curve

$$D_s(OSR) = \frac{2\sigma_q^2}{\pi}\left(\frac{\pi}{OSR} - \sin\frac{\pi}{OSR}\right) + \frac{\sigma_t^2}{OSR}$$

$$P_s = OSR \cdot p$$

$$\Rightarrow D_s(P_s) = \frac{2\sigma_q^2}{\pi}\left(\frac{\pi p}{P_s} - \sin\frac{\pi p}{P_s}\right) + \frac{\sigma_t^2 p}{P_s}$$

$$D_s(P_s) \approx \frac{p}{P_s}\left[\frac{1}{3}\left(\frac{\pi p}{P_s}\right)^2 \sigma_q^2 + \sigma_t^2\right]$$

Power-Distortion Curve -Example

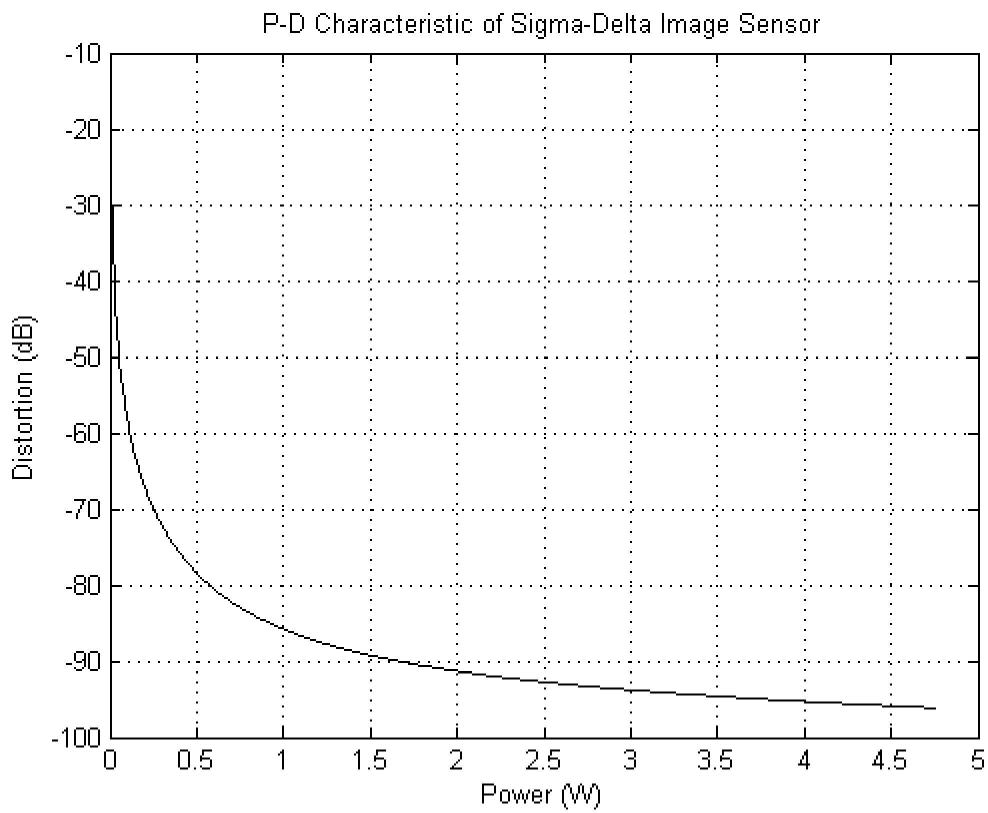


Image Sensor Bit Rate

- Dynamic range: $DR = \frac{V^2/2}{\sigma_q^2}$
- Nyquist rate ADC: $DR = 3 \cdot 2^{(2R_s - 1)}$
- Sigma-delta ADC: $DR = \frac{9OSR^3}{2\pi^2}$
- ENOB is calculated as a number of bits N that sigma-delta converter gives to achieve the same dynamic range as Nyquist rate converter with N quantization levels:

$$R_s = ENOB = \frac{9.031 \cdot \log_2(OSR) - 5.172}{6.021}$$

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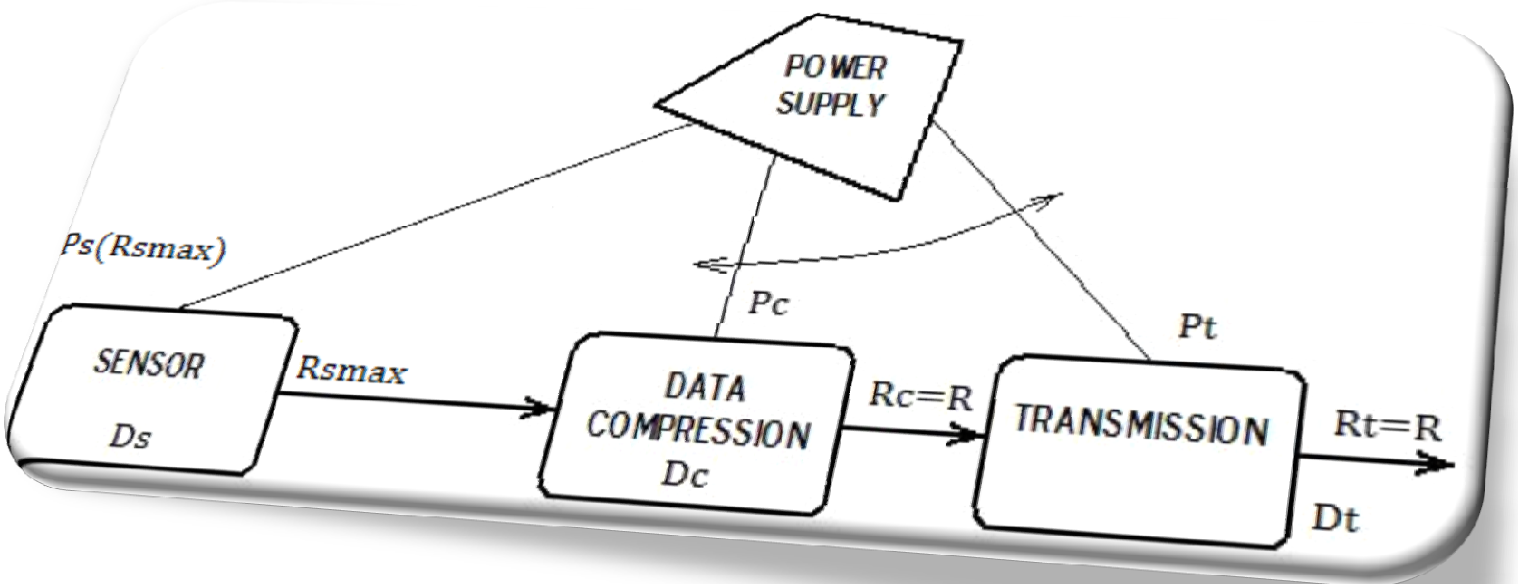
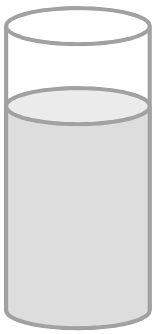
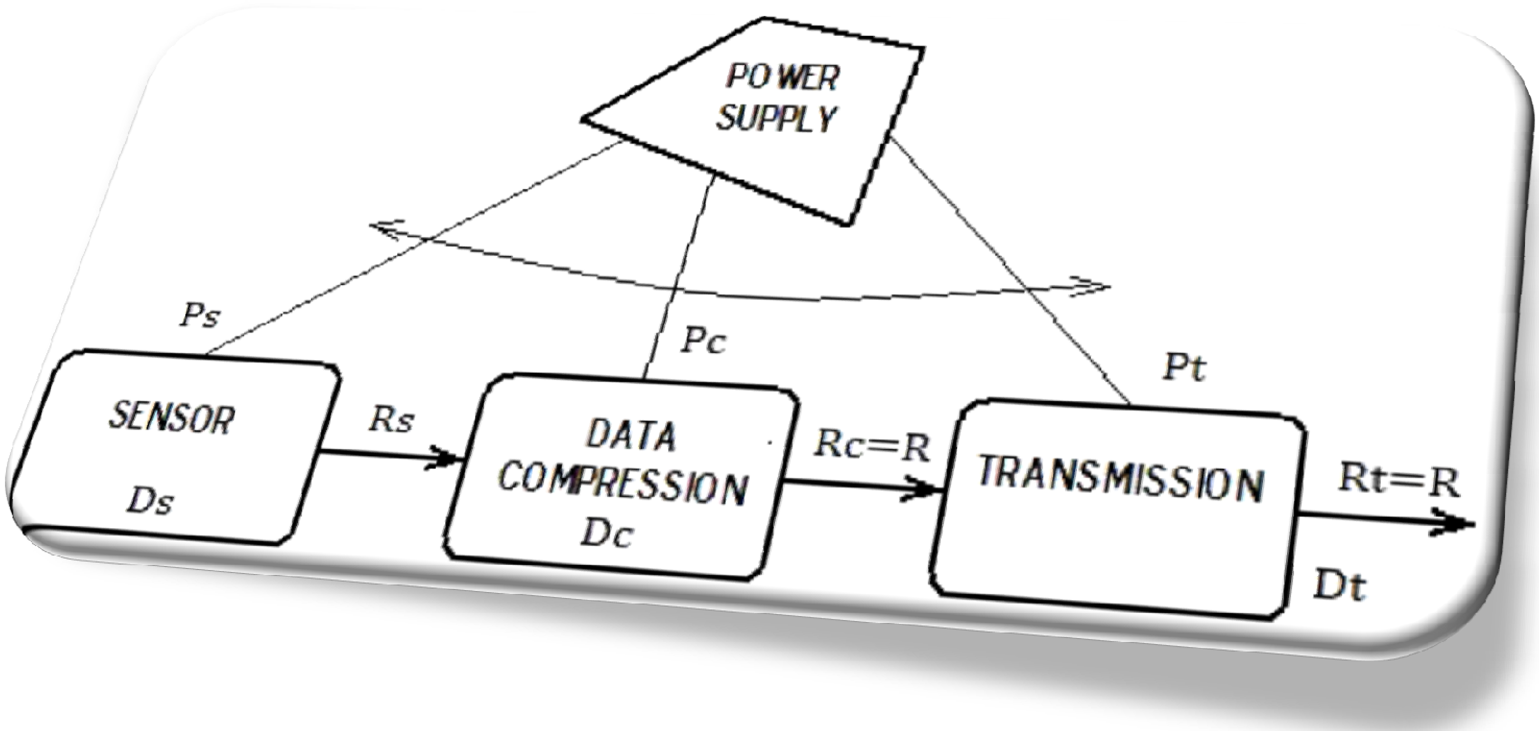
Power Control I

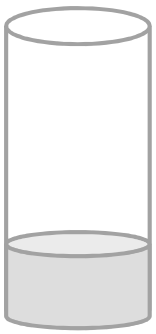


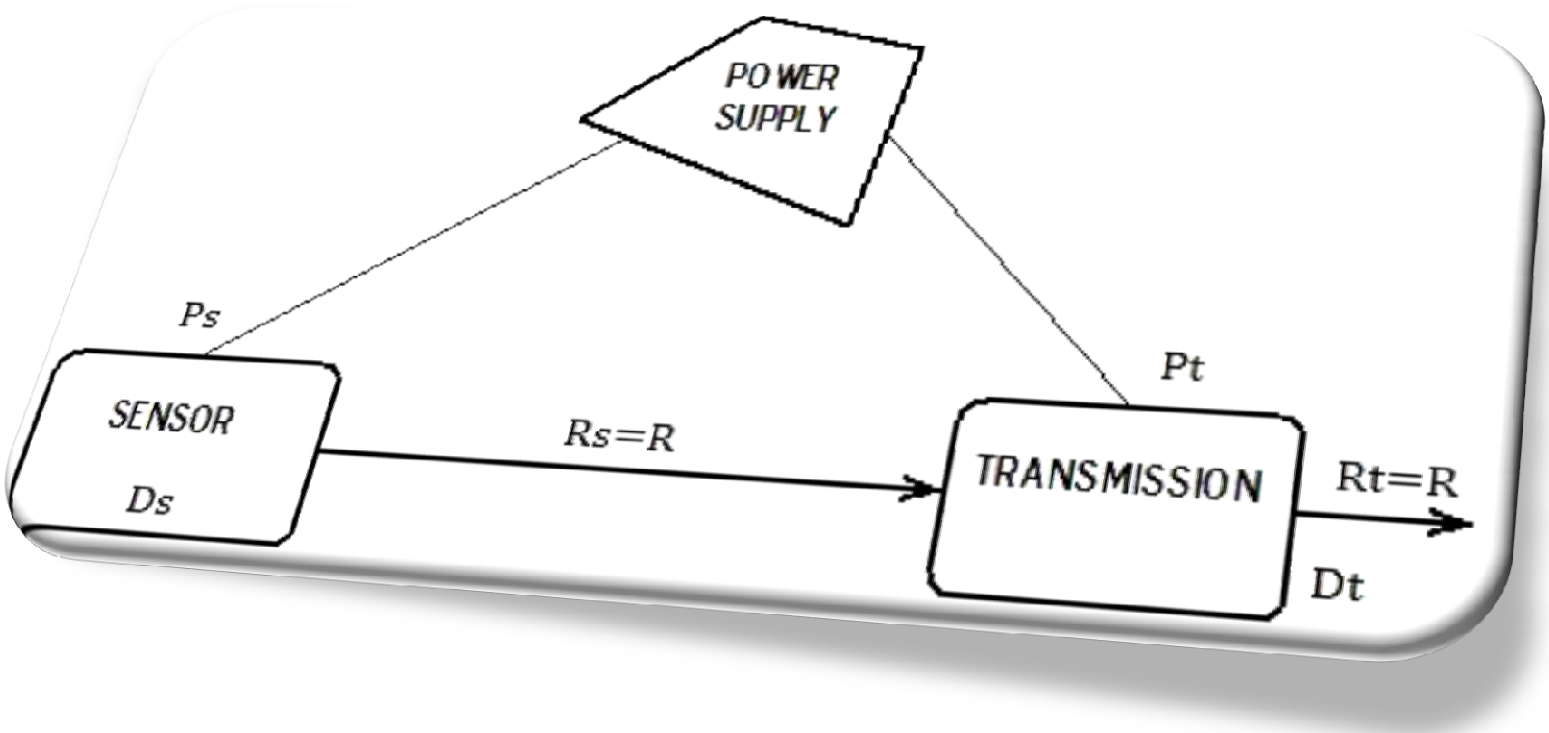
Power Control II





Power Control III





Conclusion

- Optimal power allocation for WVS is derived.
- P-R-D model of the ∑Δ imager is proposed.
- Power control stages for optimal power allocation are illustrated.

References

[1] Z.He and S.K. Mitra,"From rate-distortion analysis to resource-distortion analysis," Circuits and System Magazine IEEE, vol. 5, pp. 6-18, September 2005.

[2] Z. He and D. Wu, "Resource Allocation and Performance Analysis of Wireless Video Sensors," IEEE Transactions on Circuits and Systems for Video Technology, vol. 16, No. 5, pp. 590-599, May 2006.

[3] Z.He, Y.Liang, L.Chen,I.Ahmad, and D.Wu,"Power-rate-distortion analysis for wireless video communication under energy constraints," IEEE Transactions on Circuits and Systems for Video Technology, vol. 15, No.5, pp. 645-658, May 2005.

[4] Z.He,W.Cheng, and X.Chen,"Energy minimization of portable video communication devices based on power-rate-distortion optimization," IEEE Transactions on Circuits and Systems for Video Technology, vol. 18, No.5, pp. 596-608, May 2008.

[5] Z.Ignjatovic and M.Bocko, "A 0.88nW/pixel, 99.6dB linear-dynamic-range fully-digital image sensor employing a pixel-level sigma-delta ADC," VLSI Simposium, 2006.

[6] D. Maricic, Z.Ignjatovic, and M. Bocko, "Low power, high dynamic range CMOS image sensor employing pixel-level oversampling analog to digital conversion," unpublished.

[7] P.M. Aziz, H.V. Sorensen, and J. vn der Spiegel, "An overview of sigma-delta converters," IEEE Signal Processing Magazine, vol. 13, No. 1, pp. 61-84, Januar 1996.