Generalised link-layer adaptation with higher-layer criteria for energy-constrained and energy-sufficient data terminals

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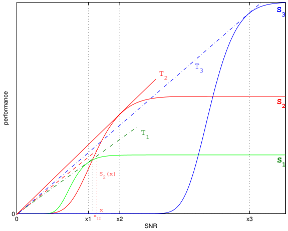
ISWCS, 19-22 Sep 2010, York, UK

Executive Overview

- Link-layer parameters (modulation, packet size, coding, etc) should be (adaptively) optimised
- Typical approach: choose modulation to maximise spectral efficiency (bps/Hertz) with bit error rate (BER) constraint
- For packet communication, higher-layer criteria are better
- We find the link-layer configuration for maximal “goodput”
- Limited and unlimited energy supplies studied separately

- the key: a tangent line from (0,0) to the scaled packet-success rate function (PSRF) graph (PSR = 1 minus PER)
- the steeper the tangent (greater slope) the better the configuration
- true whenever PSRF is an “S-curve”



Idealised packetised communication system

- TX makes L-bit packets including C error-detection bits ($L - C$ information bits)
- Each packet transmitted symbol by symbol (e.g., M-QAM)
- W-bandwidth flat-fading channel adds white noise
- Received packet goes through ideal error detector (CRC)
- RX sends positive or negative acknowledgement (ACK/NACK) over idealised feedback channel
- TX re-sends packet until it gets the corresponding ACK

Link configuration criteria

- Link-layer configuration: (adaptively) choose modulation, bits per symbol, packet length, code length, power
- Possible optimisation criteria:
  - Spectral efficiency : maximise bits/second/Hertz with bit error rate constraint
    (Webb, 1995 [1]); (Chung & Goldsmith, 2001 [2])
  - "Goodput" : maximise total information bits transferred over a period of interest, e.g., bits per second, or bits per Joule
    (Goldsmith, Goodman, et al., 2006 [3]); present work
  - network utility maximisation (NUM): maximise an index of network performance (e.g., sum of each link performance) with average power constraint
    (O'Neill & Goldsmith, 2008 [4])

Goodput-optimal link configuration

- (Goldsmith, Goodman, et al., 2006 [3]) proposes it for
  - single communication link
  - M-QAM modulation
  - error-detecting codes (CRC)
- performance index: (net) throughput (goodput), given by

$$T = \frac{L - C}{L} b R_s f(b, \gamma_s, L) \tag{1}$$

  - L, C : packet length, CRC length in bits
  - b , R_s bits per symbol, symbol rate
  - γ_s : *per symbol* signal-to-noise ratio.
  - $f(b, \gamma_s, L) = [1 - P_b(\gamma_s, b)]^{L/b}$ packet-success rate (1 - PER)
  - $P_b(\gamma_s, b)$ *symbol*-error probability
- Basic idea: choose parameters that maximise T

Issues with analysis in reference

- [3]'s algebraic approach requires PSRF in explicit formula
- Such formulae valid only under strong assumptions, and/or major simplifications, and for very specific systems
- Expressions barely tractable. Approximation for M-QAM:

$$T = \frac{L-C}{L} bR_s \left[1 - 4(1-2^{-b/2}) Q \left(\sqrt{\frac{p}{N_0 R_s} \left(\frac{3}{2^b - 1} \right)} \right) \right]^{L/b}$$

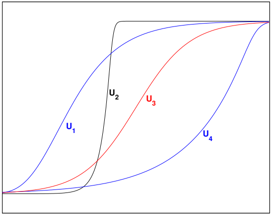
with $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp(-\frac{1}{2}t^2)dt \Leftarrow$ NO explicit solution!

- Certain technical steps seem controversial:
  - all parameters are treated as continuous (even bits/symbol)
  - derivatives are taken with respect to them
- Solutions are hard to interpret; general lessons elusive

Generalised packet-success rate function

We drop algebra in favour of analytical geometry:

- *for link* parameters, $\mathbf{a}$, & symbol-SNR x, $F(x;\mathbf{a})$: packet-success rate. Ex: $F(x;\mathbf{a}) = [1 - P_b(x,b)]^{L/b}$, $\mathbf{a} = (L,b)$
- For technical reasons, $f(x;\mathbf{a}) := F(x;\mathbf{a}) - F(0;\mathbf{a})$ replaces F
- Assume the graph of $f(x;\mathbf{a})$ has the S-shape shown
- S-curves are very general ("almost" concave, convex, linear, "ramps" etc)



Link configuration criteria for data terminals

- Criteria for data terminal: maximise total number of information bits transferred over period of interest, τ
  - with unlimited energy, set τ as time unit
    $\Longrightarrow$ info bits/second ("goodput") maximisation
  - with energy budget E, τ is "battery life" (E/p if power=p)
    $\Longrightarrow$ info bits/Joule maximisation
- Transferred info bits in τ secs, with PSR $f(\gamma_s; \mathbf{a})$:

$$\tau \frac{L-C}{L} bR_s f(\gamma_s; \mathbf{a}) \tag{2}$$

Maximising information bits per Joule

Fact

The max no. of transferred info bits with configuration $\mathbf{a}$*, energy* E*, & normalised ch gain* h *is* $(hE)S(x^*;\mathbf{a})/x^*$ *where S-curve* $S(x;\mathbf{a}) := ((L-C)/L)bf(x;\mathbf{a})$*, &* x^* *maximises* $S(x;\mathbf{a})/x$

- with power p, SNR $x = hp/R_s$, & energy lasts $\tau = E/p$
- By (2), the number of transferred info bits in τ secs is

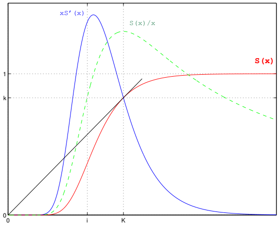
$$\frac{E}{p}\frac{L-C}{L}bR_s f(hp/R_s;\mathbf{a}) \equiv hE\frac{L-C}{L}b\frac{f(hp/R_s;\mathbf{a})}{hp/R_s} \equiv hE\frac{S(x;\mathbf{a})}{x} \tag{3}$$

- hE is fixed; $\therefore$ the SNR that maximises $S(x;\mathbf{a})/x$ is optimal.
- For a given configuration, $b(L-C)/L$ is a constant. $\therefore S(x;\mathbf{a}) \propto f(x;\mathbf{a})$, & if f is an S-curve, so is S.

The maximiser of S(x)/x

Fact

If S is an S-curve, then, (i) $S(x)/x$ has a unique maximum, (ii) found at the tangency point ("genu") of the "tangenu" (unique tangent line from (0,0) to the graph of S)



Proof.

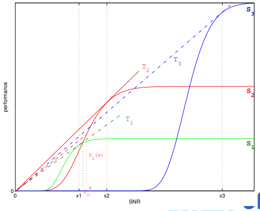
See [5] □

Most energy-efficient link configuration

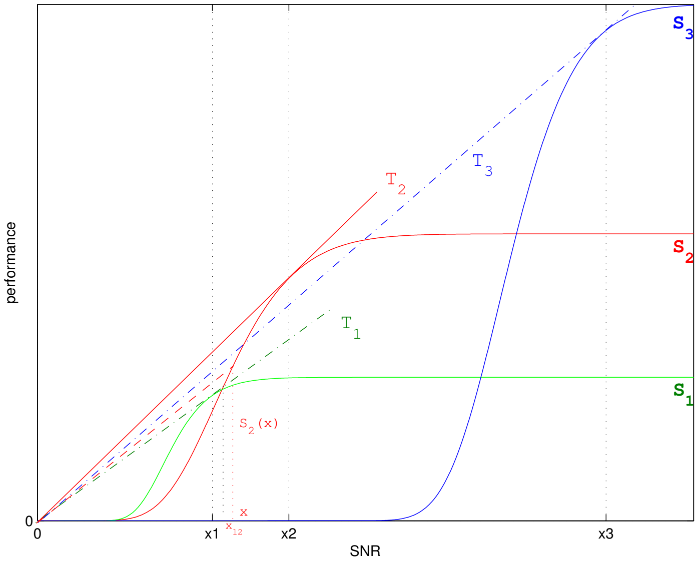
Theorem

For each configuration $\mathbf{a_i}$*, let* $S(x;\mathbf{a_i}) = ((L-C)/L)bf(x;\mathbf{a_i})$*. If* $\mathbf{a_{j^*}}$ *maximises transferred info bits per Joule, then* $S(\cdot;\mathbf{a_{j^*}})$ *has the steepest tangenu among considered configurations*

- By previous Facts :
  (i) terminal maximises $(hE)S(x;\mathbf{a_i})/x$
  (ii) maximiser is x_i^* (at tangency point)
- $\therefore$ max no. of transferred info bits:
  $(hE)S(x_i^*;\mathbf{a_i})/x_i^*$
- $\therefore$ configuration with greatest ratio
  $S(x_i^*;\mathbf{a_i})/x_i^*$(steepest tangenu) is best



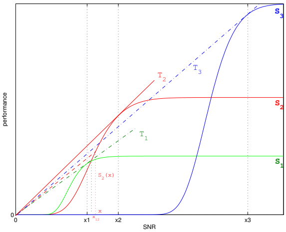
The steeper the tangent the better the configuration



Recapitulation

- Previous work recognises the importance of link configuration (modulation, packet size, coding, etc) under higher-layer criteria for packetised communication
- But it necessitates explicit formulae and controversial technical steps, which limits its applicability
- Present work is grounded on analytical geometry; it postulates that the PSRF is an S-curve, and from this, it yields a sharp and general result:

- The steeper the tangent from (0,0) to the (scaled) PSRF graph (an S-curve) the better the configuration
- S-curves include most (if not all) PSRF of interest. $\therefore$ result is highly applicable
- Battery-fed terminal discussed; similar result for unlimited energy is in paper



Limitations/Outlook

- Results obtained “off line” can be put in device’s memory, for link re-configuration through simple table look-ups
- Developing such tables is possible research path
- “Best effort” (data) traffic assumed. Similar analysis for media traffic (video) is in progress
- Point-to-point transmission studied. Of interest: to embed analysis in network model, such as [4]’s.

Thank You!

Questions?

Maximising goodput (unlimited energy supply)

Fact

The max goodput with configuration $\mathbf{a}$*, power limit* $\hat{p}$ *& normalised ch-gain* h *is* $h\hat{p}S(x^*;\mathbf{a})/x^*$ *where S-curve* $S(x;\mathbf{a}) := ((L-C)/L)bf(x;\mathbf{a})$*, &* x^* *maximises* $S(x;\mathbf{a})/x$

- Unlimited energy $\implies$ optimal $p = \hat{p}$ (max power)
- SNR $x = h\hat{p}/R_s \implies R_s = h\hat{p}/x$
- By (2), the number of transferred info bits over 1 sec is

$$\frac{L-C}{L} bR_s f(h\hat{p}/R_s;\mathbf{a}) \equiv h\hat{p}\frac{L-C}{L} b\frac{f(x;\mathbf{a})}{x} \equiv h\hat{p}\frac{S(x;\mathbf{a})}{x} \quad (4)$$

- $h\hat{p}$ is fixed; $\therefore$ the SNR that maximises $S(x;\mathbf{a})/x$ is optimal
- For a given configuration, $b(L-C)/L$ is a constant. Thus, $S(x;\mathbf{a}) \propto f(x;\mathbf{a})$, & if f is an S-curve, so is S
- $\therefore$ main theorem also applies under unlimited energy

Link configuration goodput trade-offs

- Goldsmith/Goodman[3] 's performance index

$$T = \frac{L-C}{L} bR_s[1 - P_b(\gamma_s, b)]^{L/b}$$

$$\text{for M-QAM, } P_b \approx 4(1-2^{-b/2})Q\left(\sqrt{\frac{hp}{R_s}\left(\frac{3}{2^b-1}\right)}\right)$$

  $\gamma_s = hp/R_s$: symbol SNR; p: power; h: ch gain over noise
- Assume C held constant (e.g. $C = 16$ bits)
- Some trade-offs:
  - L increases $(L-C)/L$ but reduces PSR=$[1 - P_b(\gamma_s, b)]^{L/b}$
  - b raises "raw" bps,bR_s, but lowers energy/bit (& PSR)
  - R_s increases raw bps but reduces γ_s & hence PSR
  - power raises SNR(& PSR) but lowers "battery life", if appl.

For Further Reading I

- W. Webb and R. Steele, “Variable rate QAM for mobile radio,” *Communications, IEEE Transactions on*, vol. 43, pp. 2223–2230, Jul 1995.
- S. T. Chung and A. Goldsmith, “Degrees of freedom in adaptive modulation: a unified view,” *Communications, IEEE Transactions on*, vol. 49, pp. 1561–1571, Sep 2001.
- T. Yoo, R. J. Lavery, A. Goldsmith, and D. J. Goodman, “Throughput optimization using adaptive techniques.” Available: `http://wsl.stanford.edu/Publications/Taesang/`, 2006.

For Further Reading II

- D. O'Neill, A. Goldsmith, and S. Boyd, "Optimizing adaptive modulation in wireless networks via utility maximization," in *Communications. IEEE International Conference on*, pp. 3372–3377, May 2008.
- V. Rodriguez, "An analytical foundation for resource management in wireless communication," in *Global Telecommunications Conf., IEEE*, vol. 2, pp. 898–902 Vol.2, Dec. 2003.