Energy Efficiency Limits of Load Adaptive Networks

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Abstract: Based on traffic models the energy consumption of adaptive networks is compared to networks with constant power consumption. The results show that adaptive network resource allocation serves to reduce the energy consumption of networks significantly.

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1. Introduction

Although there are significant variations in the network traffic load over time, current telecommunication networks operate at a nearly constant power consumption, since they are mostly designed to peak bit rate demands in current building practice [1]. Due to these traffic variations adaptive networks that allocate network resources according to actual traffic demands are expected to offer a promising opportunity for designing energy-aware networks.

In general, there are times of activity and inactivity of networks, components and device on different timescales [6], [7], [2] ranging from a seasonal over a weekly and daily behavior down to variations in the region of sub-seconds on chips. If networks, components and devices would be able to follow these traffic variations in a way that they activate and deactivate resources for processing and transmission according to the actual needs, there is a huge energy saving potential expected. Therefore limits are of interest, to what extent load adaptive networks are able to increase the energy efficiency. Based on traffic observations, models are established for service-specific and aggregated traffic, respectively. The energy consumption is calculated, if adaptive networks follow these traffic characteristics resulting in an energy efficiency limit compared to constant-power reference networks.

2. Traffic volume observation and modeling

The traffic volume in telecommunication networks varies considerably over time, which can be observed in service-specific (Fig. 1 a), b)) and in aggregated (Fig. 1 c)) traffic. There are huge usage and traffic variations ranging from peak values at certain daytimes – in the evening – towards about 25% (aggregated) or about 5% (service-specific) in the morning. In order to get insights on the potential benefits of load adaptive networks concerning energy efficiency, approximate traffic volume models according to the observed traffic characteristics are developed.

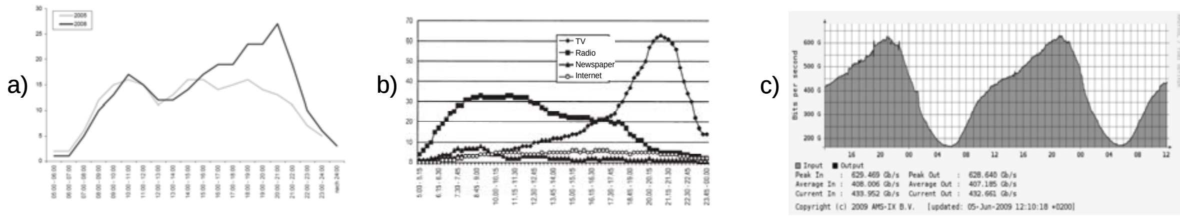

Fig. 1. Media usage and traffic volume observation: a) Daily internet usage in Germany 2005/2008 [7], b) daily media usage in Germany 2005 (in percent) [3], c) daily traffic volume at Amsterdam internet exchange [6]

The traffic characteristic of service-specific internet usage (Fig. 1 a)) is modelled as a piecewise linear function

$$V_1(t) = \begin{cases} V_{\min} & \text{for} \quad 0 \le t < 6T/24 \\ 3\left(V_{\max} - V_{\min}\right)\dfrac{t}{T} - \dfrac{1}{4}\left(3V_{\max} - 7V_{\min}\right) & \text{for} \quad 6T/24 \le t \le 10T/24 \\ \dfrac{6}{5}\cdot\left(V_{\max} - V_{\min}\right)\dfrac{t}{T} + V_{\min} & \text{for} \quad 10T/24 \le t \le 20T/24 \\ -6\left(V_{\max} - V_{\min}\right)\dfrac{t}{T} + \left(6V_{\max} - 5V_{\min}\right) & \text{for} \quad 20T/24 \le t \le 24T/24 \end{cases}, \tag{1}$$

(Fig. 2 a)) with V_{max} and V_{min} as the maximum and minimum traffic volumes, respectively, occurring during the time T = 24 h of a day in all cases. The service-specific TV traffic is modeled as a modified F distribution [5] function

$$V_2(t) = V_{min} + (V_{max} - V_{min}) \cdot \left[a^{\frac{a}{2}} b^{\frac{b}{2}} \frac{\Gamma\left(\frac{a}{2}+\frac{b}{2}\right)}{\Gamma\left(\frac{a}{2}\right)\Gamma\left(\frac{b}{2}\right)} \cdot \frac{\left(\frac{-t-T_1}{T_2}\right)^{\frac{a}{2}-1}}{\left(a\left(\frac{-t-T_1}{T_2}\right)\right)^{\frac{a+b}{2}}} \right] \quad (2)$$

with $\Gamma(x)$ as the Gamma function [4] as well as $T_1 = T/4$, $T_2 = 25/24T$, a = 21 and b = 21 (Fig. 2 b)). The characteristics $V_3(t)$ of aggregated traffic during a day can be approximated by a sinusoidal function (Fig. 2 c)):

$$V_3(t) = \frac{1}{2}(V_{max} + V_{min}) + \frac{1}{2}(V_{max} - V_{min}) \cdot \sin\left(\frac{2\pi}{T} t\right). \quad (3)$$

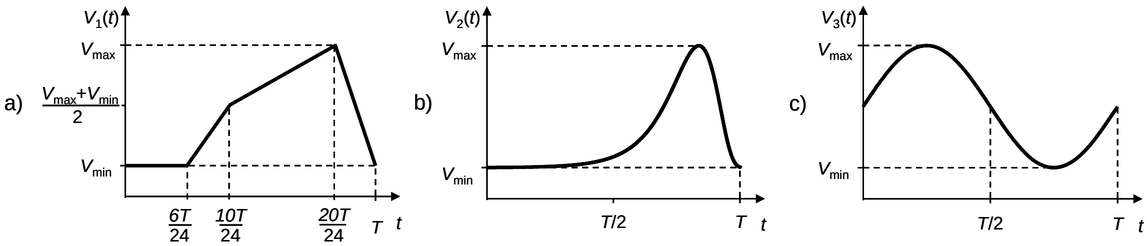

Fig. 2. Daily traffic models: a) $V_1(t)$ corresponding to observations in [7] for service-specific internet traffic, b) $V_2(t)$ corresponding to observations in [3] for service-specific TV traffic, c) $V_3(t)$ corresponding to observations from [6] for aggregated traffic

3. Power and energy consumption of load adaptive networks

The reference network is assumed to operate at a constant peak power P_{max} reflecting current network building practice: $P_0(t) = P_{max}$ (Fig. 3 a)). A significant increase in network's energy efficiency is expected, if the power consumption exactly follows the traffic demands, resulting in a daily power characteristic according to

$$P_n(t) = K \cdot V_n(t)\,, \quad (4)$$

with direct proportionality between the traffic volume $V_n(t)$ – measured in bit/s – and the power $P_n(t)$ (in W) with respect to (1), (2), and (3). The constant K turns out to be a power per bit rate or – equivalently – an energy per bit.

Such fully adaptive networks are expected to be difficult to design, plan and operate. From a practical point of view solutions would be beneficial, which aim at an energy efficiency increase using a simpler pragmatic approach resulting in an exemplary stepwise power characteristic for the network with aggregated traffic $V_3(t)$ (Fig. 3 a)):

$$P_4(t) = \begin{cases} P_{max} & \text{for} \quad 0 \le t < T/2 \\ 0{,}5 \cdot (P_{max} + P_{min}) & \text{for} \quad T/2 \le t \le T \end{cases}. \quad (5)$$

During time T the network consumes the energy $E_n = \int_0^T P_n(t)\, dt$. The energy results are summarized in Table I.

4. Energy efficiency limits

For calculating the energy-saving potential of load adaptive network resource allocation, the energy efficiency parameter $\varepsilon_n = E_n/E_0$ is defined describing the energy efficiency increase of the different network variants compared to the reference network: A minimum ε indicates a maximum energy saving compared to the reference network, whereas a maximum ε, i. e. ε = 1, indicates no energy efficiency increase at all. The solutions for the energy efficiency parameters are summarized in Table I and their graphs are shown in Fig. 3 b) as functions of P_{min}/P_{max}.

Table I. Energy efficiency parameters for the different network characteristics

	$n = 0$ (reference)	$n = 1$ (service-specific, internet)	$n = 2$ (service-specific, TV)	$n = 3$ (aggregated, fully adaptive)	$n = 4$ (aggregated, stepwise adaptive)
E_n	$P_{max} \cdot T$	$\frac{T}{48}(21P_{max} + 27P_{min})$	Numerical integration	$\frac{T}{2}(P_{max} + P_{min})$	$\frac{T}{4}(3P_{max} + P_{min})$
ε_n	1	$\frac{1}{48}\left(21 + 27\frac{P_{min}}{P_{max}}\right)$	Numerical solution	$\frac{1}{2}\left(1 + \frac{P_{min}}{P_{max}}\right)$	$\frac{1}{4}\left(3 + \frac{P_{min}}{P_{max}}\right)$

There is a direct proportionality between the energy efficiency parameter ε_n and the ratio of the minimum and maximum power P_{min}/P_{max} (Fig. 3 b)) – i. e. V_{min}/V_{max}. For small values P_{min}/P_{max} the highest energy savings are enabled by the adaptive network variants, whereas for higher P_{min}/P_{max} the energy-saving potential decreases.

The characteristics of the service-specific traffic give the opportunity to operate at about 43% (internet) or 25% (TV) of the energy of the reference network, respectively, in the best case $P_{min}/P_{max} = 0$. Current exemplary service-specific network usage is in the range of $V_{min}/V_{max} = 0.05$ (Fig. 1 a) and b)) and therefore the network could operate at $P_{min}/P_{max} = 0.05$, as shown in Fig. 3 b): Then a fully adaptive network with respect to internet usage operates at about 44% of the energy of the reference network (56% saving) and the TV network at about 26% (74% saving).

In case of aggregated sinusoidal traffic with a fully adaptive network one half of the energy is consumed compared to the reference network in the best case $P_{min}/P_{max} = 0$. The more pragmatic stepwise adaptive network allows for an energy saving of even 25% enabling significantly reduced energy consumption with a much simpler approach. Current exemplary networks with aggregated traffic are in the range of $V_{min}/V_{max} = 0.25$ (Fig. 1 c)) and therefore could operate at $P_{min}/P_{max} = 0.25$, (Fig. 3 b)). Then the fully adaptive network operates at about 62% of the energy of the reference network (38% saving) and the stepwise adaptive network even at about 81% (19% saving).

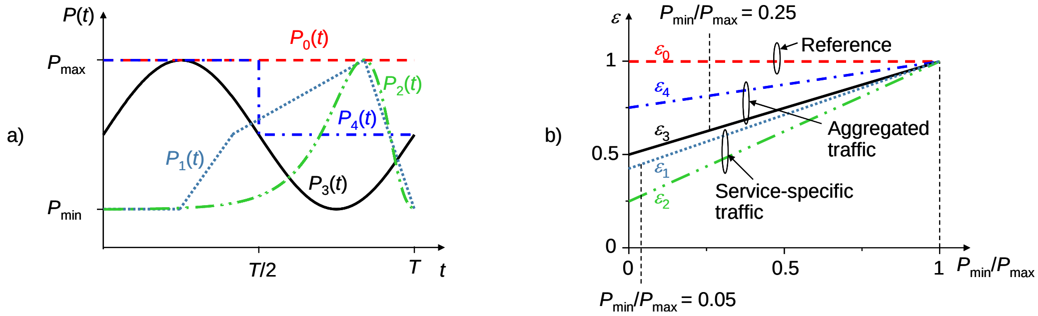

Fig. 3. a) Different power characteristics $P(t)$ as functions of the time t , b) energy efficiency ε_n as functions of the power ratio P_{min}/P_{max}

5. Conclusion

Based on network traffic characteristics the energy saving potential of load adaptive networks was studied with respect to a reference network with constant power usage in order to obtain energy efficiency limits. The energy saving potential of adaptive networks very strongly depends on the traffic dynamics: In general, per-service networks allow for higher energy efficiency improvements than networks carrying aggregated traffic. From the energy perspective dynamic load adaptive network operation is expected to result in significant improvement.

6. References

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