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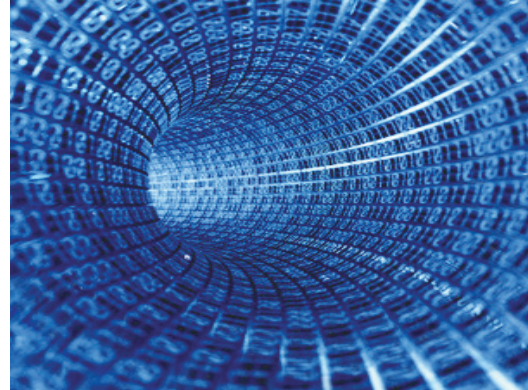
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Power Versus Bandwidth Efficiency in Wireless Communications: from Economic Sustainability to Green Radio

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Abstract: We carry out a comprehensive analysis of a range of wireless network efficiency considerations. Firstly, we explore the properties and the implications of the power- versus bandwidth-efficiency criteria. Secondly, we perform a detailed top-down analysis of a typical commercial wireless network, which emphasizes the inherent differences between the aforementioned two efficiency metrics, while demonstrating that the appropriate choice of the network optimization criterion can have a profound effect on the overall network performance. Finally, we address the issue of resource management and its impact on the definition of the overall system efficiency. Our results suggest that no substantial area spectral efficiency gains beyond those exhibited by the 2G cellular technology may be economically achieved, and hence, no significant economic gains may be realized by simply increasing the bps/Hz bandwidth efficiency. In contrast, manifold utility and throughput gains as well as substantial Quality of Service enhancements may be attained by the appropriate combi-

nation of improved power efficiency, bandwidth expansion as well as the appropriate evolution of the networking paradigm.

Key words: green radio; economic aspects of wireless communications; bandwidth versus power efficiency

1. INTRODUCTION

Wireless communications constitute a thriving trillion-dollar global industry of vast scale and socio-economic significance. The continuous investment in research and development, aimed at improving the utility and the efficiency of wireless communications networks, brings about a wealth of theoretical knowledge and practical engineering solutions. Remarkably, however, a widely accepted choice of a criterion characterizing the overall efficiency of a wireless network remains an open problem[1]. By definition, efficiency is a quality that character-

izes the correspondence between the consumed resources and the attained utility. Clearly, therefore, the notion of efficiency is intricately related to the contextual definition of the utility as well as the specific method of attributing value and cost to the resources available. In the context of wireless communications, we may identify the two attributes of the wireless electromagnetic medium, namely the frequency spectrum and the power, as the two major resource categories.

On one hand, many researchers consider bandwidth efficiency as the principal efficiency criterion[2]. This tendency is vividly reflected by the abundance of standards, such as the High-Speed Packet Access (HSPA)[3] and the IEEE 802.11n as well as the 802.16 and 3GPP LTE[4] systems complemented by a large body of theoretical studies proposing transceiver schemes exhibiting an ever-increasing bits-per-second-per-Hertz (bps/Hz) throughput, while sometimes overlooking the associated area spectrum efficiency, power consumption and complexity-related issues. The bandwidth efficiency criteria is largely motivated by the assumption of strict limitations on the available bandwidth, which are further stimulated by the assumption of the spectrum being a scarce resource. As pointed out in [1, 5], however, the scarcity of spectrum is an artificial constraint inflicted by the currently prevailing attitude to spectrum management.

On the other hand, a host of spread-spectrum methods intentionally sacrifice the bps/Hz performance for the sake of achieving a better bit-per-second-per-Watt (bps/W) power efficiency, typically accompanied by lower levels of spectrum contamination, as well as by an increased robustness against the interference[6-9]. By no means should these methods be classified as less efficient, since in the appropriate circumstances they are capable of considerably improving the overall performance of the entire network.

In order to further emphasise the importance of the problem considered, we would like to point out some of the pressing socio-economic issues, which require a prompt attention of the engineering com-

munity. Each of the major mobile carriers currently consume in excess of 50MWatt of power to support their respective cellular network infrastructures in the UK alone. At the time of writing, the cost of the power consumed constitutes a substantial factor in the financial bottom line of all major mobile carriers. While the business model assumed by these commercial entities may still be economically viable, this might no longer be the case in the future. With the costs of energy rapidly rising as well as the growing awareness of the associated environmental impact, the effective cost of the excessively bandwidth-efficient but interference-sensitive signalling strategies may become prohibitive.

Against this background, in this paper we carry out a comprehensive analysis of a range of wireless network efficiency considerations. Specifically, in Section II we explore the properties and the implications of the aforementioned power versus bandwidth efficiency criteria. In Section III we carry out a detailed top-down analysis of a typical commercial wireless network, which emphasizes the inherent differences between the aforementioned two efficiency metrics, while demonstrating that the appropriate choice of the optimization criterion can have a profound influence on the overall network performance. Our conclusions are summarized in Section IV.

II. POWER VERSUS BANDWIDTH EFFICIENCY

Let us commence our discourse by recalling the fundamental capacity upper-bound of a communication system quantified by the Shannon-Hartley theorem[10], which postulates

$$R < B \log_2(1 + \gamma_s) \quad (1)$$

where B denotes the number of complex degrees of freedom per second available for communication, while γ_s is the average Signal-to-Noise Ratio (SNR) recorded at the receiver. Equation (1) describes the capacity of a Gaussian channel, assuming an infinite duration of the transmitted signal, as

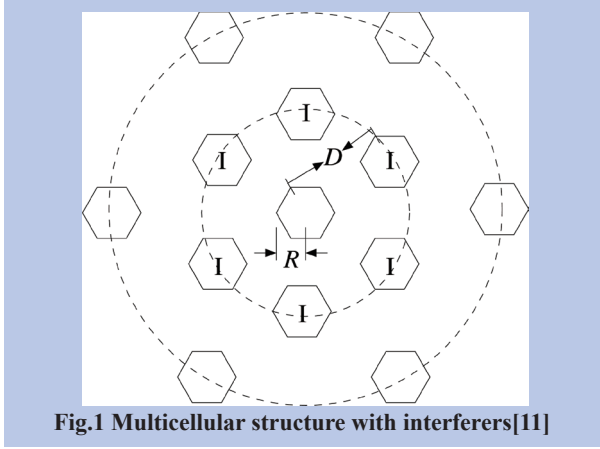


Fig.1 Multicellular structure with interferers[11]

well as an infinite detection/decoding complexity. It is important to underline the universality of (1), which applies to both single- and multiple-antenna systems, as well as to fading channels characterized by arbitrary distributions. Importantly, the strict inequality sign in (1) holds in any realistic communication system.

Subsequently, we define the bandwidth efficiency v_b of a communication system as the number of bits per channel use (bpcu), where a single channel use corresponds to one complex degree of freedom available for communications¹, as well as the power efficiency v_p as the number of bits per thermal noise energy unit (TNEU), where TNEU refers to the amount of signal energy identical to the variance of the complex-valued AWGN samples recorded at the receiver. From (1) we may conclude that

$$v_b < \log_2(1 + \gamma_s) \quad (2)$$

while

$$v_p = \frac{v_b}{\gamma_s} < \frac{\log_2(1 + \gamma_s)}{\gamma_s} \quad (3)$$

for any realistic communication system.

Moreover, in most practical scenarios characterized by various performance-limiting factors including channel fading, interference as well as latency and complexity constraints, the actual attainable bandwidth and power efficiencies are considerably lower than that predicted by Equations (2) and (3). For instance, in the case of uncorrelated Rayleigh fading channels, (2) becomes[12]

$$v_b < \frac{1}{\log 2} e^{1/\gamma_s} \text{Ei}(1/\gamma_s) \quad (4)$$

where we define $\text{Ei}(x) = \int_x^\infty \frac{e^{-t}}{t} dt$. Furthermore, in order to exemplify the impact of interference on the achievable data-rate upper bound, let us consider the simple interference model devised in [11, 13] and shown in Figure 2. Specifically, we assume an idealized hexagonal cell structure comprised by cells of radius R and frequency reuse cell-clusters of size N_f , which further implies having six significant interferers at a distance of $D = \sqrt{3N_f}R$ [11, Chapter 14]. Following [11], we assume a logarithmic path-loss model, as well as receiving an approximately equal power $I_k = (R/D)^\gamma S$ from all six first-tier interferers, where S denotes the signal power, while γ is the pass-loss exponent. The resultant Signal-to-Interference Ratio (SIR) may be expressed as

$$\text{SIR} = \frac{S}{\sum_{k=1}^6 I_k + N_0} = \frac{\gamma_s}{1 + 6(3N_f)^{-\gamma/2} \gamma_s} \quad (5)$$

where N_0 denotes the PSD of the local noise.

The efficiency upper bounds corresponding to the Gaussian and Rayleigh channel scenarios of Equations (2), (3) and (4) as well as the corresponding upper bounds for the interference-limited scenario of Equation (5) are depicted in Figure 2. It is evident that the efficiency criteria v_b and v_p are inherently different and may not be maximized simultaneously. Specifically, as seen in Figure 2, any transmission scheme, characterized by a bandwidth efficiency, which exceeds 1bps/Hz/antenna exhibits a substantial degradation in terms of the corresponding power efficiency. Observe, that while the higher values of the frequency reuse cluster size N_f tend to mitigate inter-cell interference and thus result in improved “local bandwidth efficiency”, the corresponding area spectral efficiency, which is inversely proportional to the cluster size N_f is substantially reduced.

We would like to conjecture that an appropriate trade-off between the efficiency metrics v_b and v_p has to be found for the sake of maximizing the network’s overall utility, as defined below. In the

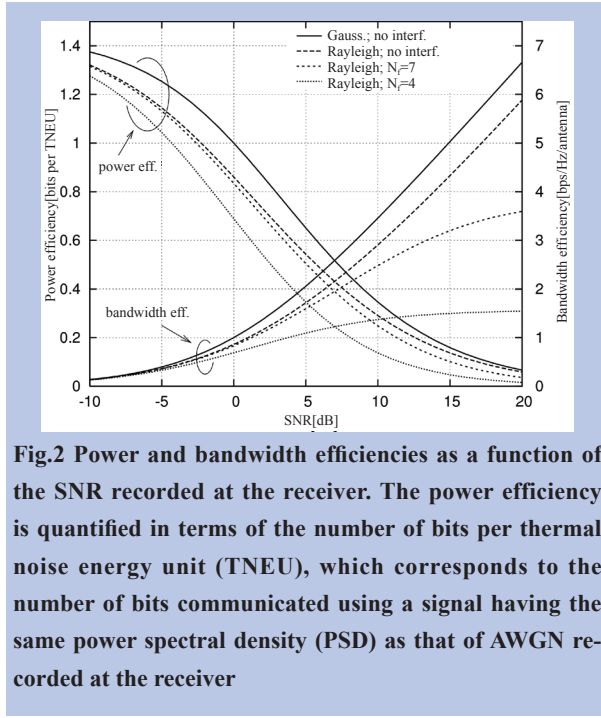


Fig.2 Power and bandwidth efficiencies as a function of the SNR recorded at the receiver. The power efficiency is quantified in terms of the number of bits per thermal noise energy unit (TNEU), which corresponds to the number of bits communicated using a signal having the same power spectral density (PSD) as that of AWGN recorded at the receiver

following section we would like to elaborate on the importance of the appropriate choice of efficiency criteria and its corresponding impact on the network's utility with the aid of an example.

III. TOP-DOWN ANALYSIS

Let us consider a commercial entity X , whose main business is the provision of wireless communications services to a diverse body of end-users. We will use the average monetary profit K expressed in monetary units² per second as the major criterion of the company's performance. Using the most basic economic principle we may suggest that the profit K may be formulated as the revenue minus the actual cost of the services provided. Specifically, let us define the average revenue per second as a function $A(R)$ of the total rate R (in bits per second) of successfully communicated information over the entire network of carrier X . Likewise, we can quantify the running cost per second as $C_p P + C_r = B(P_{RF} + P_c) + C_r$, where the factors C_p and P denote the cost per Wattsecond (Ws=joule) and

the total average power (in Watts) consumed by the carrier's network, while the coefficient C_r denotes the cumulative rate of all additional costs not related to the power consumption, including the hardware investment and maintenance costs, as well as the spectrum licensing costs. Consequently, we arrive at the following expression

$$K = A(R) - C_p P - C_r \quad (6)$$

Firstly, we may conjecture that the total power P_{RF} dissipated by the RF equipment employed by the carrier's infrastructure may be expressed in terms of the average SNR γ_s required to achieve reliable communications at the target data-rate of R . More specifically, we may formulate $P_{RF} = \alpha B \gamma_s N_0$, where the coefficient α denotes the transmission chain's overall efficiency, which takes into account, for instance, the power efficiency of the RF equipment, such as the frequency conversion and power amplification efficiency as well as the average link budget, including the Tx/Rx antenna gains and path loss. Furthermore, the quantity B denotes the network's effective total bandwidth, which equals to the product of the total number of cells comprising the carrier's network and the average utilized channel bandwidth per cell. In other words, B corresponds to the total number of complex degrees of freedom per second available for the carrier's transmissions. Finally, we would like to emphasise that at the fundamental level of discrete binary computing, each binary operation executed by any of the processing units employed by the network infrastructure requires an amount of energy safely exceeding the energy of thermal noise. In fact, state-of-the-art computers typically operate at an effective SNR of 100dB and more³. Correspondingly, we can reformulate the total power consumed by the computing equipment employed by the network as $P_c = B \beta \omega N_0$, where the coefficient β constitutes a unitless quantity, which denotes the ratio between the average amount of energy required to execute a single binary operation and the power spectral density (PSD) of the thermal noise. In other words, the coefficient β quantifies the effec-

tive power efficiency of the signal processing (SP) and computing hardware employed by the carrier's network. Furthermore, the complexity-per-channel-use ω quantifies the algorithmic efficiency of the signal processing software utilized by the network, while the resultant product $\beta\omega$ quantifies the overall power efficiency of the entire hardware-software infrastructure. Moreover, we would like to point out that in the context of digital signal processing, the effective SNR γ_s and the associated complexity-per-channel-use ω are closely related through the operation of quantisation invoked in the process of the analog-to-digital conversion. Specifically, the extra bits required to describe a high-fidelity signal at the input of the detector as well as the corresponding higher number of information bits at the detector's output inflict a substantial increase in the processing complexity. Although a rigorous proof of our conjecture is beyond the scope of this study, it is plausible simplifying assumption to suggest that in a well-designed bandwidth-limited communication system, the complexity-per-channel-use ω may be assumed to be linearly proportional to the SNR γ_s . Specifically, in currently operational cellular networks the RF transmission power accounts for approximately 20% of the total power consumption[14]. We may therefore conjecture that $\alpha\gamma_s=4\beta\omega$ and thus the total consumed power of Equation (6) may be simply expressed as $P=5\alpha\gamma_s BN_0$.

Subsequently, based on the general principles of commercial communication networks and network economics[15], we may conjecture that the revenue $A(R)$ is linearly proportional to the number of active subscribers N_u and logarithmically proportional to the average data-rate provided for each user⁴. Consequently, taking into account the aforementioned fact that the utility K is defined up to multiplication by a currency-related factor and using the Shannon-Hartley theorem of Equation (1), we may formulate the following expression

$$K = N_u \log_2 \left(1 + \frac{B_u}{R_u} \log_2(1+\gamma_s) \right) - C_p \cdot 5\alpha\gamma_s BN_0 - C_r \quad (7)$$

$$= \frac{B}{B_u} \log_2 \left(1 + \frac{B_u}{R_u} \log_2(1+\gamma_s) \right) - C_p \cdot 5\alpha\gamma_s BN_0 - C_r \quad (8)$$

where we define the average bandwidth per active user as $B_u=B/N_u$ and the baseline data-rate per user as \bar{R}_u . Let us elaborate a little further by defining the utility-per-channel-use as $k=K/B$, which yields

$$k = \frac{1}{B_u} \log_2 \left(1 + \frac{B_u}{R_u} \log_2(1+\gamma_s) \right) - C_p \cdot 5\alpha\gamma_s N_0 - \frac{C_r}{B} \quad (9)$$

Note that both the per-channel-use quantities γ_s and k constitute bandwidth-normalized versions of the per-second quantities P and K . Using Equations (8) and (9) we would like to explore the relationship between the network's utility K and three major network characteristics, namely the total consumed power P , the total effective bandwidth B , as well as the average user throughput R_u . More specifically, Figure 3 depicts the utility-per-channel-use k evaluated from Equation (9) as a function of the average SNR γ_s . Observe that the resultant function $k(\gamma_s)$ of Figure 3 exhibits a single global maximum. Although the specific result depicted in Figure 3 was calculated using the set of assumptions based on the UK's GSM network statistics summarized in Table 1, it may be readily verified that any sensible choice of network characteristics has a limited impact on the general shape and on

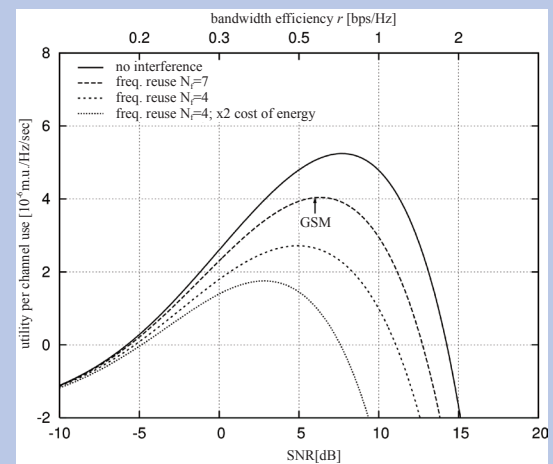


Fig.3 Network utility per channel use of Equation (9) versus average SNR based on AWGN Shannon capacity and GSM network economy statistics

the properties of the function $k(\gamma_s)$ as well as on the corresponding function $K(P)$. We may thus surmise that the utility achievable by any bandwidth-limited communication network is ultimately upper-bounded and there exists an average SNR as well as a corresponding power consumption point, where the network's utility is maximized.

To elaborate further, Figures 4 illustrates the relationship between the network's utility K and the total effective bandwidth B as well as the average user data-rate R_u characterized by Equations (8) and (9). Once again, the results depicted in Figure 4(a) are based on the statistical characteristics of the UK's GSM network[14, 16, 18]. Nevertheless, the general conclusions suggested by the results of Figure 4(a) are readily applicable to a wide range of scenarios, including the 3G[3] as well as LTE networks[4]. The network's utility versus the total effective bandwidth B is characterized in Figure 4, where the three curves describe the following three distinctive scenarios.

In the first scenario we assume the number of users N_u in Equation (8) to remain constant, while the total effective bandwidth B and the corresponding average user data-rate R_u are increased. In this case, a certain network utility gain may be expected as a result of the increased revenue associated with the improved data-rate per user. As was mentioned earlier, however, based on the general con-

siderations as well as the available statistics, one can expect an increase in revenue, which is only logarithmically proportional to the corresponding increase in the per-user data-rate. In other words, an average customer is ready to pay only a small additive premium for a multiplicative increase in the attainable data-rate. This trend is clearly demonstrated by the service rates associated with mixed 2G and 3G cellular networks. On the other hand, the cost of power consumed remains linearly proportional to the occupied bandwidth, if the power spectral density of the transmitted signal is assumed to be constant. As a result, as may be seen in Figure 4(a), the network utility gain saturates and thereafter rapidly declines, once the associated power consumption costs outweigh the potential revenue gains. For instance, the network operator's profit increases by approximately 4%, when the total effective bandwidth is doubled from 100GHz to 200GHz, while the power consumed and the corresponding cost to the operator is clearly doubled, or in other words increased by 100% as a result.

Subsequently, in the second scenario we assume the average data-rate per user R_u to remain constant, while the total effective bandwidth B and the associated number of users N_u are increased in Equation (8). Evidently, this case corresponds to the hypothetical scenario, where the pool of potential users willing to join the network is unlimited. Cor-

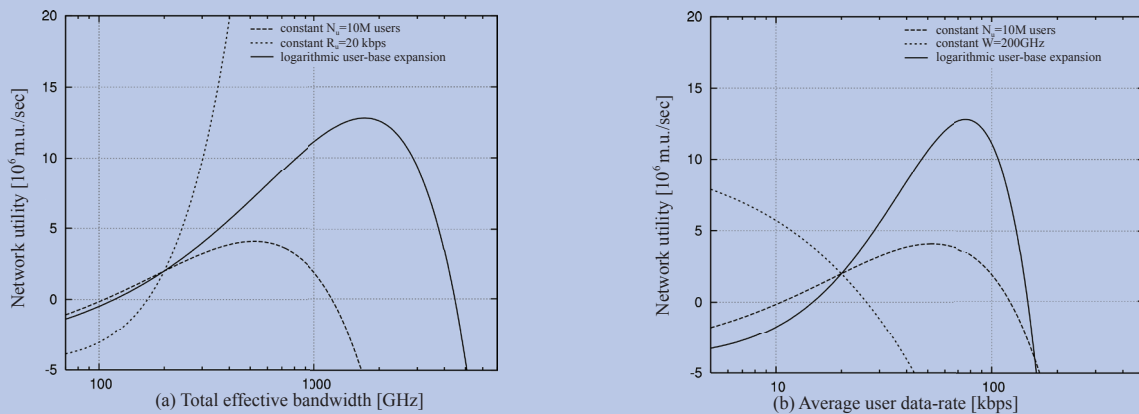


Fig.4 Network utility of Equation (8) versus the total effective bandwidth (a) and the average user data-rate (b) based on AWGN Shannon capacity and GSM network statistics

Table 1 GSM network characteristics

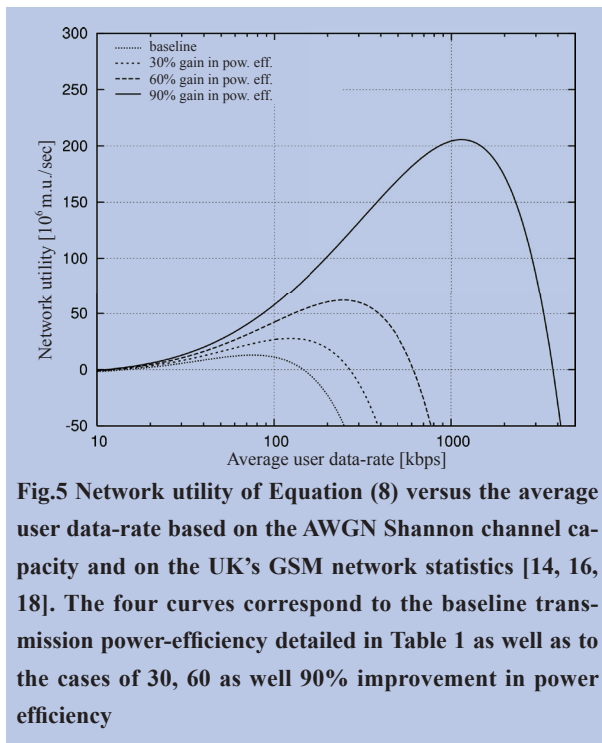
Quantity	Value	Assumptions
Effective value of information	1.54 p/Mbit	20 pound per month for 60min at 12kbps per day [14]
Cost of energy	$C_p=0.0028$ p/kWs	10p per kWh [16]
Additional costs	$C_r=0.5B$	Additional costs amount to the total of 50% of the revenue generated at a current rate of 0.2 bps/Hz/cell
Transmission efficiency	$\alpha=0.005$ mWs	10% of 20MHz 1kW BS required for 6 dB SNR [17]
Computational efficiency	$\beta w=4\alpha\gamma s$	The actual power consumed by the RF transmission amounts to approximately 20% of the total carrier's power consumption [14]
Total effective bandwidth	$B=200$ GHz	$10,000 \times 20$ MHz base-stations

respondingly, the number of users N_u increases linearly with the bandwidth B and therefore results in a virtually unlimited increase in the network's utility K . Naturally, this scenario is not realistic, since the pool of potential users is typically limited.

Finally, we consider a more realistic scenario, characterized by the third curve in Figure 4(a), where we make the assumption that a higher data-rate R_u entails a higher functionality and a correspondingly higher appeal to the users, thus resulting in a certain expansion of the user-base. As the simplest possible intuitively plausible assumption, we deem the number of users N_u to be a logarithmic function of the average data-rate R_u . Namely, we have $N_u = \bar{N}_u \log_2(1 + R_u / \bar{R}_u)$ in Equation (8), where the parameters \bar{N}_u and \bar{R}_u are the number of users and the corresponding average data-rate based on the UK's current GSM network statistics[16, 18, 19]. As seen in Figure 4(a), a substantial utility gain may be attained by increasing the effective bandwidth B . Nevertheless, similarly to the scenario of having a fixed user population N_u , the maximum attainable utility is ultimately upper-bounded and tends to decline rapidly, when the bandwidth corresponding to the maximum-utility point is exceeded. For instance, the network operator's profit increases by approximately 7%, when the total effective bandwidth is doubled from 1000 GHz to 2000 GHz, while the power consumed and the corresponding cost to the operator is clearly doubled, or in other words increased by 100% as a result.

Similar trends may be identified, when considering the relationship between the network's utility K and the average user data-rate R_u , as evaluated from Equation (8) and depicted in Figure 4(b). More specifically, the three curves seen in Figure 4(b) correspond to the scenarios assuming a fixed number of user N_u , a constant effective bandwidth B as well as the aforementioned logarithmic data-rate-related user-base expansion scenario. Likewise, the attainable network utility saturates and then declines rapidly, when the number of users is assumed to be constant. Furthermore, increasing the user throughput proves to be inherently disadvantageous for the network, if the total effective bandwidth is assumed to be fixed. Finally, a substantial, but necessarily upper-bounded utility gain is possible, if a logarithmic data-rate-related increase in the number of users may be assumed.

Subsequently, we would like to characterize the attainable network utility K as a function of the power efficiency coefficient α in Equation (8). More specifically, Figure 5 depicts the network utility K from Equation (8) versus the average user rate R_u for the transmission efficiency values detailed in Table 1 as well as for 30, 60 and 90% improvements in the overall power efficiency. Once again, in Figure 5 we stipulated the aforementioned assumption of logarithmic data-rate-related user-base expansion. From the results depicted in Figure 5 we may conclude that both the maximum attainable network utility K as well as the corresponding average user data-rate R_u may be improved virtu-



ally indefinitely by improving the network's power efficiency, while gradually expanding the total effective bandwidth and the corresponding size of the user-base.

Based on the implications of Equations (8) and (9) augmented by the results depicted in Figure 3, 4(a) and 5 we would like to summarize the following conjectures:

1. The utility achievable by any realistic communication network characterized by a fixed power efficiency is ultimately upper-bounded.
2. For any set of three values selected from the network $\{B, P, N_w, R_u\}$ there exists a unique value of the fourth parameter, for which the $K(B, P, N_w, R_u)$ is maximized.
3. In any bandwidth-limited communication network a substantial network utility gain may only be achieved by improving the underlying power-efficiency.
4. The only sustainable way of increasing the network's utility is constituted by a combination of improved power efficiency accompanied by bandwidth expansion.

It is important to emphasize that the ten-fold expansion of the total effective bandwidth as well as the 90% power efficiency gains hypothesised in Figure 4(a) and 5, respectively, might not be realistically achievable in the context of the current socio-economical conditions. Specifically, the prevalent combination of command and control and property rights based spectrum management models[1] imposes an artificial resource-limited ecosystem, which tends to favour monopolistic non-cooperative business strategies, accompanied by a host of suitable technological solutions. In particular, the presently predominant cellular network topology, which is characterized by a centralised resource management and rigid hierarchy of non-cooperating communicating nodes, is a prominent manifestation of a system optimized for a resource-limited environment[20]. Ultimately, we would like to speculate that a gradual transition towards regulated open access spectrum management models[1], facilitating the employment of short-range ultra-wideband low-power and low-complexity reconfigurable cooperative networking[21], has the potential to sustain the substantial utility gains suggested in Figure 4(a), 5 and thus guarantee the successful long-term development of the wireless communications industry.

IV. CONCLUSIONS

In this paper we have emphasised the importance of power efficiency considerations in the context of the design and optimization of wireless communication networks. We provided formal definitions of power as well as bandwidth efficiencies and explored their relative importance using a detailed top-down analysis of a typical commercial wireless network. Our results suggest that no substantial area spectral efficiency gains beyond those exhibited by the 2G cellular technology may be economically achieved. Moreover, no significant economic gains may be realized by simply increasing the bps/Hz bandwidth efficiency. In contrast,

manifold utility and throughput gains as well as substantial Quality of Service (QoS) enhancements may be attained by the appropriate combination of improved power efficiency, bandwidth expansion as well as the conclusive evolution of the networking paradigm. 中国通信

Notes

1. Observe that in a case of single-antenna systems bpcu corresponds to bits-per-second-per-Hertz (bps/Hz), while in multiple-antenna scenarios bpcu is equivalent to bits-per-second-per-Hertz-per-antenna, where the number of antennas, or spatial links is determined by the minimum between the numbers of transmit and receive antenna elements.
2. The profit, synonymously also referred to as the utility function K is defined as a normalized quantity, which has to be multiplied by a baseline charge per user per second quantified in arbitrary monetary units, such as US dollars, UK pounds etc.
3. $\approx 10\text{Watt}$ for a single-core 32-bit 1GHz processor, which yields $\approx 40\text{dBm} - (20 + 90 - 174)\text{dBm} = 104\text{dB}$.
4. Here we assume that higher prices may be charged for premium data-rates and the relationship between the increased data-rates and the corresponding extra charges is logarithmic.

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References

- [1] G. Gow and R. Smith, *Mobile and Wireless Communications: An Introduction*. Open University Press/McGraw-Hill, 2005.
- [2] A. Goldsmith and S.-G. Chua, "Variable-rate variable-power MQAM for fading channels," *IEEE Transactions on Communications*, vol. 45, pp. 1218–1230, 1997.
- [3] L. Hanzo, J. Blogh, and S. Ni, 3G, HSDPA, HSUPA and

FDD Versus TDD Networking: Smart Antennas and Adaptive Modulation. IEEE Press-John Wiley, February 2008.

- [4] L. Hanzo, J. Akhtman, and M. Jiang, *MIMO-OFDM Turbo-Transceivers for LTE, WIFI and WIMAX*. IEEE Press-John Wiley, 2010.
- [5] K. Werbach, "Open spectrum: The new wireless paradigm," New America Foundation Working Paper, October 2002. [Online]. Available: http://werbach.com/docs/new_wireless_paradigm.htm
- [6] A. Viterbi, *CDMA: Principles of Spread Spectrum Communication*. MA, USA: Addison-Wesley, June 1995
- [7] S. Verdú, "Spectral efficiency in the wideband regime," *IEEE Transactions on Information Theory*, vol. 48, no. 6, pp. 1319–1343, 2002.
- [8] M. Benedetto and G. Giancola, *Understanding Ultra Wide Band Radio Fundamentals*. Prentice Hall, 2004.
- [9] L. Hanzo, L.-L. Yang, E.-L. Kuan, and K. Yen, *Single- and Multi-Carrier DS-SS-CDMA. 1em plus 0.5em minus 0.4em* John Wiley and IEEE Press, 2003, 430 pages.
- [10] E. Shannon, "A mathematical theory of communication," *Bell System Technical Journal*, vol. 27, pp. 379–423 and 623–656, June and October 1948. [Online]. Available: <http://plan9.bell-labs.com/cm/ms/what/shannonday/shannon1948.pdf>
- [11] L. Hanzo, S. X. Ng, T. Keller, and W. Webb, *Quadrature Amplitude Modulation: From Basics to Adaptive Trellis-Coded, Turbo-Equalised and Space-Time Coded OFDM, CDMA and MC-CDMA Systems*. John Wiley & Sons, 2004, 1036 pages.
- [12] J. Li, A. Bose, and Y. Zhao, "Rayleigh flat fading channels' capacity," in *Proceeding of the 3rd Annual Communication Networks and Services Research Conference*, May 2005, pp. 214–217.
- [13] W. C. Y. Lee, "Spectrum efficiency in cellular [radio]," *IEEE Transactions on Vehicular Technology*, vol. 38, no. 2, pp. 69–75, May 1989.
- [14] Ericsson, "Sustainable energy use in mobile communications, White paper," December 2007. [Online]. Available: <http://www.ericsson.com/technology/whitepapers> =0pt
- [15] A. Nagurney, *Network Economic: A Variational Inequality Approach*, second and revised ed. Dordrecht, The Netherlands: Kluwer Academic Publishers, 1999.
- [16] DBIRR, "Quarterly energy prices," Department of Business Interprise & Regulatory Reform, A National

Statistics Publication, Tech. Rep., March 2008. [Online]. Available: <http://www.berr.gov.uk/files/file45393.pdf>

[17] J. Lempiäinen and M. Manninen, Radio Interface System Planning for GSM/GPRS/UMTS, Kluwer Academic, 2003.

[18] R. Steele, C.-C. Lee, and P. Gould, GSM, cdmaOne and 3G Systems. 1em plus 0.5em minus 0.4em John Wiley and Sons, 2001.

[19] T. Halonen, J. Romero, and J. Melero, GSM, GPRS and EDGE Performance. Evolution Towards 3G/UMTS. John Wiley and Sons, 2003.

[20] D. MacKenzie, "The collapse of civilisation," New Scientist, pp. 29–35, April 2008.

[21] K. Werbach, Radio Revolution: The Coming Age of Unlicensed Wireless. New America Foundation, 2003. [Online]. Available: <http://werbach.com/docs/RadioRevolution.pdf>

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