Energy-efficient Multiaccess Dissemination Networks

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Abstract—Previous efforts to improve energy efficiency focused on different network architecture components, aiming in particular at increasing the operational time of battery-powered devices. This paper argues that patching elements of the current Internet architectural paradigm are not sufficient for achieving major savings in the overall network energy consumption. After reviewing the main characteristics of current Internet use, including the proliferation of broadband wireless and mobile networks and the overwhelming role of dissemination traffic, this paper examines their impact on energy consumption and studies alternative WMAN scenarios. Simulation results indicate that adopting a multiaccess information-centric approach, can halve the overall access network energy consumption and deliver the same level of functionality to a larger number of Internet devices.

I. INTRODUCTION

According to estimates, “the Internet” may by consuming more than 860 TWh annually [1]. The total electricity use for servers worldwide in 2005, including cooling and auxiliary equipment, was roughly 123 TWh, while the direct electricity consumption was 61 TWh according to [2]. Fettweis and Zimmermann [3] summarize more ICT energy use estimates and report that the Vodafone Group radio access network alone consumed nearly 3 TWh in 2006. While it is hard to validate any such estimates, they do indicate the increased interest in the topic, as ICT energy use has been evidently on the rise.

NGNs are more flexible in their operation than traditional networks and thus may achieve significant reductions in energy use [4], but their deployment is not panacea. This paper reviews the current state of the art in the Internet and focuses on the impact of wireless and mobile broadband proliferation and current traffic trends on energy consumption. After noting that multiaccess overlapping networks are becoming the norm, it becomes evident that there is a need for a global energy-aware dissemination network. The main contribution of this paper is a first evaluation of the potential for reducing the carbon footprint of wireless metropolitan area networks (WMANs) by adopting a multiaccess information-centric approach. The simulation results indicate that if different WMAN technologies are used, possibly across operators, in a cooperative [5], [6] instead of an antagonistic manner, the overall network access carbon footprint can be halved without loss of functionality.

This paper is organized as follows. Section II reflects on the impact to energy consumption due to the proliferation of WMANs, the rapid increase in broadband penetration and the associated Wi-Fi access point deployment, and the dominance of dissemination networking. Section III presents a simulation study of alternative WMAN deployment scenarios and their corresponding energy use. Section IV discusses the challenges lying ahead with respect to energy consumption, contemplates other proposals for energy efficient WMAN design and operation, and candidly lists the limitations of this study. Finally, Section V concludes this paper and outlines future work.

II. DISSEMINATION IN MULTIACCESS NETWORKS

The UMTS Forum web site lists more than 220 UMTS/W-CDMA networks in 100 countries. In the EU, it is common to have several operators covering an area in an overlapping manner. Mobile WiMAX deployments are also expected to cover major areas soon. Overlapping coverage has many facets, one of which is energy consumption: the relative ease of deploying wireless networks leads at times to network resource oversupply, a redundancy that increases the overall ICT carbon footprint. Louhi and Scheck highlight that for cellular networks the radio access part is the most energy consuming [7]. Reportedly, the associated expenditure is comparable to the personnel cost for maintaining the network [3].

According to Cisco estimates [8], the average Western European mobile broadband subscriber recorded monthly traffic of 856 MB in 2007. Cisco expects that this average will grow almost five-fold to more than 4 GB by 2012. For comparison, the respective estimates for fixed-line usage are 3 GB in 2007 and 18 GB by 2012. Video will play a dominant role in this traffic increase, and can only be handled by fresh infrastructure investments and thus even bigger electricity bills for operators. Some expect fierce competition between 3GPP and non-3GPP technologies for WMAN domination. Still, it is well known that operators have been sharing sites and base stations in 2G/3G deployments, opting for coopetition, that is, competing as a rule but cooperating in certain areas in order to provide better service to the public [6]. Before exploring this further in Section III, we examine the energy use due to broadband and Wi-Fi AP deployments and the emergence of dissemination networking, which both call for a new architectural paradigm.

A. The Proliferation of Residential Broadband Access

Residential broadband is typically accompanied by a possibly password-protected Wi-Fi access point (AP), which is preconfigured to remain always on. APs may feature rudimentary power saving mechanisms, but these are often rendered ineffective due to their reliance on traffic load detection and timeouts: in general, at least one household device uses the network throughout the day [9]. As even more devices will
use household WLANs in the near future, all APs in the apartments of Fig. 1 would be always powered on. What is more, for several reasons, each AP is meant to be used solely by the subscriber household devices. In Fig. 1, George could connect with both his own AP at a high bit rate and the one on the floor below at a lower rate. Helen, living one floor down, however, cannot connect to her own AP at a high rate due to signal fading and interference. She can only connect to either of the APs at medium bit rates. If the two APs were managed in an energy-conserving manner, Helen’s AP could be turned off automatically till she can take advantage of the higher bit rate. Even if both Helen and George have the same operator, all broadband-service bundled APs are managed separately and not as a comprehensive wireless access network.

Considering city-wide deployments, there are more than 12 276 operational Wi-Fi APs in London; New York City and Paris follow with a total of 9 227 and 4 481 APs, respectively [10]. Given that the population in London is approximately 7.5 million people, there is one AP per 611 residents. In Oulu, the open access panOULU network has deployed 1 048 APs, which translates into a “density” of 124 residents per AP. Of course, accounting for all commercial and home APs, for which no data is available, would increase this AP density.

With the price of Wi-Fi equipment decreasing, it is not far-fetched to anticipate that by 2013 many cities and towns world-wide will have large AP densities. AP proliferation will increase further the overall ICT carbon footprint. With an average power consumption per AP of, say, 6 W, as is the case for the NETGEAR MR814, each AP remaining always on consumes 53 kWh annually. Its carbon footprint is 26 kgCO₂ for the NETGEAR MR814, each AP remaining always on average power consumption per AP of, say, 6 W, as is the case the increase further the overall ICT carbon footprint. With an AP density of 26 kgCO₂eq. A conservative estimate for the annual electricity consumption by the aforesaid London APs is 645 MWh. The corresponding carbon footprint may be in excess of 322 tCO₂eq, counting only AP operation. If the world in 2015 (est. pop. 7 billion) attains the average panOulu AP density in 2008, then a total of 56.4 million APs will be consuming nearly 3 TWh per year, emitting approximately 1.5 MtCO₂eq. This is greater than the world-wide Vodafone Group radio access network electricity use in 2006 [3]. In other terms, it is 5% of the direct 2005 server world electricity consumption, excluding cooling and auxiliaries [2]. This is an unfavorable development. New network architectures will be crucial in reducing electricity bills, carbon footprints, and Wi-Fi pollution.

B. The Emergence of Dissemination Networks

Jacobson [11] points out that the Internet is used as it was originally designed to be used only as an exception to the rule. Indeed, the vast majority of Internet traffic is actually dissemination of information, not point-to-point information exchange. It is quite well established that peer-to-peer, web and video-on-demand (VoD) akin to YouTube dominate the traffic mix, although there are contradictory reports about which traffic type is the most popular. According to Ellacoya [12] “web traffic” took over as the dominant traffic source, mainly due to the success of YouTube, in June 2007. Other recent reports, see [13], for example, indicate that P2P is by far more popular. Either way, P2P, Web, and VoD combined have consistently comprised 85% or more of the traffic mix for years. Jacobson’s argument is clear: we are running dissemination networks using methods from a conversational paradigm.

Early signs of the rift between what is being carried and how it gets delivered were seen with the introduction of the WWW, a dissemination network by definition. Web pages, although actually distinct information objects pointed to by a URI, are assembled by opening several TCP connections. Caching and HTTP keep-alives soon came to the rescue, at least partially. But, with 20/20 hindsight, this was simply an attempt to retrofit dissemination into the conversational paradigm of end-to-end TCP connections. The ability to create new objects by cross-linking and now develop new applications via mash-up elements means that objects may be stored in different places, possibly replicated. In a digital universe, there is little reason why one copy of the information is the “original” and the rest mere replicas, and thus the originating host ought to be consulted with always. Yet, this is the current state of the art in web-based dissemination, even if commercial content distribution networks (CDNs) are taken into consideration.

P2P overlays create a different type of CDN and have evolved to deliver VoIP, IPTV, VoD and software, beyond the infamous file swaps of the early 2000s. In P2P CDNs there is no longer one “true source” for each available object, as integrity can be verified. Nonetheless, although content takes center stage, P2P still relies on a host-centric paradigm. Topology-agnostic P2P overlays have contributed significantly to traffic growth during the last years and, in an effort to evade operator control, may actually be responsible for a significant proportion of the overall ICT carbon footprint. Application traffic patterns matter for energy consumption: maintaining a list of peers up-to-date with keep alives, assisting peers till tit-for-tat algorithms determine that the peer needs to be “choked” as it does not contribute accordingly, and relying solely on end-to-end metrics to achieve reliability and performance targets, all increase energy consumption. Hosts left on overnight to complete downloads, render ineffective proposals which attempt to capitalize on diurnal patterns as Wi-Fi APs and other network access infrastructure cannot go into sleep mode.
Moreover, P2P networks tend to include connections between hosts far apart and do not take advantage of locality, although this may change in the future [14]. Thus, proposals for shutting down parts of the Internet infrastructure can also be defeated by applications that receive no information from the network and are not designed with energy awareness to begin with.

C. Towards a Network of Information

The EU-funded project 4WARD (www.4ward-project.eu) has recently presented a set of scenarios which motivate the introduction of a new Future Internet (FI) architectural paradigm called Network of Information (NetInf) [15]. In short, a case is made for taking information per se as the starting point, and designing a communication infrastructure which is much better adapted to the task of distributing and exchanging information compared to today’s host-centric approach. NetInf extends the concept of identifier/locator split with another level of indirection and decouples the self-certifiable objects from their storage location(s). In contrast with P2P, though, NetInf is not meant to become a topology-unaware overlay architecture.

Fig. 2 illustrates a scenario that involves two overlapping WMANs. Take the case of WiMAX/3G multiaccess node R receiving a video stream originating from node S. With state-of-the-art mobility management mechanisms, R can seamlessly handover between WiMAX and 3G networks, and indeed could even employ simultaneous multiaccess [16] to receive the video using both of its interfaces. However, once S and R establish their session, the two ends do not change. Assume that R handovers from 3G to WiMAX. In traditional mobility management, the path (S, Net 3, R) changes to (S, Net 3, Net 2, R); with optimization it may change to (S, Net 2, R).

But in NetInf, a further optimization is possible: the path can change to (Net 1, Net 2, R) or even simply (Net 2, R) based on information from the NetInf machinery, as the video stream, just as any other NetInf object, is not bound to any particular location and may indeed be replicated at several NetInf nodes. Due to space considerations, it is not possible to explain and elaborate further on multiaccess NetInf operation, which is introduced in [15], [17].

III. ENERGY-EFFICIENT COOPERATIVE WMANs

Take \( N = 200 \) NetInf nodes in a \( 5 \) km \( \times \) \( 1.5 \) km metropolitan area, which is covered in an overlapping manner with both mobile WiMAX and 3GPP (3G) WMANs. All nodes attempt to remain always connected while streaming a video with a target rate of 350 kb/s. In all scenarios, 40 nodes are modeled as pedestrians, 120 as users in cars, and 40 as train passengers. Automobiles and pedestrians move according to the random direction mobility model [18] while the train passes through the area on a fixed linear path. The respective velocities are \( v_s = 50 \) km/h, \( v_p = 0.5 \) m/s, and \( v_t = 60 \) km/h. The active user population density in the scenario is 26.67 users/km², which may be representative of countries such as Finland, with high penetration of broadband and cell phone access.

The mobile WiMAX (R1) baseline scenario includes five base stations (BSs), each modeled so that it can sustain a cumulative streaming rate of 10 Mb/s. The WiMAX BS transmission power is set to 58 dBm and the cell radius to 1400 m. Similarly, the 3G (R2) baseline scenario includes 27 BSs, each with a capacity of 2 Mb/s. The 3G BS transmission power is set to 43 dBm and the cell radius to 500 m. The multi-access scenario is based on the assumption that both baseline WMANs have been deployed already. Thus, all multiaccess nodes can connect to the common pool of 5 WiMAX and 27 3G BSs using the media-independent handover abstraction mechanisms detailed in [17], [19], [20]. For each scenario, we make ten independent runs, each comprising an initialization phase, which lasts 10 s, and a measurement phase, which lasts 300 s of simulated time.

At the beginning of each run, cars and pedestrians are randomly distributed throughout the city area; train passengers are randomly distributed within the confines of six train cars. We let all 200 nodes connect and move during the initialization phase and collect statistics for the remainder.

For the NetInf [15] nodes, the metrics of interest in this study are expected connection time, \( \tau \), which correlates with user satisfaction, and the number of horizontal/vertical handovers, \( m \), which correlates with the overall signaling overhead. For each node \( i \) in each simulation run \( r \) we measure its total connection time, \( t_i \), and calculate the average connection time \( \bar{\tau}_r \) across all nodes, \( \bar{\tau}_r = \frac{1}{N} \sum_{i=1}^{N} t_i \), and draw the boxplot of \( \bar{\tau}_r \) values. Similarly, we measure the number of horizontal/vertical handovers, \( \bar{m}_r \), to estimate \( m \). The last metric is WMAN energy use for a given \( \bar{\tau}_r \).

A. Mean Connection Time

First, consider the WiMAX baseline scenario. The operator can deploy 5 BS which cover the entire area but, as illustrated in Fig. 3, will not be able to deliver more than 65% mean connection time to 200 nodes. After careful planning, the operator may deploy another 2 BSs, which will increase the mean connection time to approximately 86%. Deployment of a total of eight or ten BS, will increase mean connection times to nearly 95% and 100%, respectively. The BSs in excess of the five present in the baseline scenario aim at addressing the needs of the passing train passengers and a proportion of automobiles, as pedestrians pose less of a challenge.

Then, if we consider the 3G WMAN, the baseline scenario BSs are clearly incapable of meeting the video streaming requests from 200 nodes. Although the overall capacity of
the baseline 3G WMAN is larger than the mobile WiMAX WMAN, nodes experience a mean connection time which is below 45% (see Fig. 3). Doubling the number of BSs will not double the mean connection time, although it may double the energy consumption of the wireless access network.

In the multiaccess NetInf scenario, in which each of the five WiMAX BSs is collocated with a 3G BS, the 200 NetInf nodes can actually expect a mean connection time that is nearly 90%. Assuming that baseline WiMAX and 3G WMANs deployments are in place, operator(s) can use to their advantage the multiaccess capabilities of mobile NetInf nodes, and deliver streaming videos by capitalizing on the existing infrastructure. In other words, it is possible to maintain the same power consumption envelope and more than double the mean connection time of the set of nodes considered. For the WiMAX WMAN, the savings in terms of the number of base stations deployed is in the order of 40-60%, which may translate into similar savings in operational expenditures, if one accounts for energy, maintenance, and real estate costs.

B. Handovers

Fig. 4 illustrates the average total number of handovers, \( \bar{m}_{r_v} \), across all 200 nodes. As expected, the increased mean connection time with the deployment of more BSs, for both WiMAX and 3G, is the result of the increased number of successful (horizontal, R1/R2) handovers. Fig. 4 shows that multiaccess NetInf nodes predominantly execute vertical handovers (VHO) between the two WMANs. Although the simulation code implements policies that give priority to horizontal handovers, in order to decrease signaling costs, as vertical handovers are a “heavier” operation, the results indicate that 2/3 of all handovers are vertical. That is, both WMANs have spare capacity which cannot be actually tapped in the single-access case. In contrast, multiaccess NetInf nodes can detect available resources across the two types of WMANs and increase their \( \bar{\tau}_v \). Multiaccess network selection is an NP-hard problem, so one can expect that in the coming years several heuristic algorithms will be introduced, which can be incorporated in the mobility management framework described in [19], and will further enhance multiaccess NetInf performance.

C. Energy Consumption

WMAN operators typically overprovision their coverage aiming for a certain level of mean connection time for a given size of active user population, \( N \). Louhi and Scheck [7] report that the typical BS consumes 0.5-3 kW, with newer models being far more energy efficient than older ones. Thus, the simulated baseline 3G WMAN consumes 13.5-81 kW. Assuming that mobile WiMAX BSs will consume 0.2-0.5 kW by 2010, the baseline WiMAX network would need 1-2.5 kW. Conservatively taking the lowest of these estimates, two overprovisioned WMANs, each fully capable of handling 200 nodes in the simulated area would together consume no less than 29 kW. The annual energy use would be 254 MWh, and the corresponding carbon footprint would be at least 127 tCO\(_2\)eq. Estimating the actual WMAN operating expenses (OPEX) is clearly out of scope of this study, as several parameters need to be factored in, including real estate costs.

As we saw earlier, most handovers are vertical, so multiaccess NetInf nodes are more effective in taking advantage of any spare capacity in either WMAN. In effect, with multiaccess NetInf, operators can expect to halve overall electricity use to 127 MWh and the corresponding carbon footprint to 63 tCO\(_2\)eq. Or, alternatively, deliver the video streaming services to 200 nodes while maintaining the same energy consumption envelope. If hardware efficiency defines the boundaries of BTS consumption [7], certainly the number of deployment sites defines the ceiling of WMAN energy consumption, the corresponding CO\(_2\) footprint, and OPEX. Of course, these results are indicative and not conclusive. Several aspects need to be considered, first and foremost, that modeling decisions were based on a rather abstract definition of how NetInf is anticipated to work. Even so, by taking energy use as a core performance metric from the design phase, we expect to rip significant gains down the road. As NetInf modeling advances, we expect to report more detailed results in the near future.

IV. Discussion

The information-centric, system-wide approach presented may lead to significant reduction in energy use by capitalizing on network multiaccess and coopetition. As energy consumption becomes a vital concern, continuing to deploy WMANs with significant overcapacity needs to be reconsidered. A system that allows for trading energy and service credits similar to the one used for peering traffic could be instrumental in decreasing energy consumption in future WMANs.
Earlier efforts to reduce energy consumption focused on improving the efficiency of different components of the TCP/IP stack. Recent work (see, for example, [9], [21]–[23] and the references therein) proposed methods that capitalize on multiaccess to increase the operational time of battery-powered devices, and decrease energy use in general. Further, previous work in network selection assessed operator compensation based on providing connectivity services, clearly a host-centric, end-to-end approach [6]. But no proposal was put forth for the application of information-centric, cooperative networking approaches to WMANs in order to decrease the overall energy use. Chiaraviglio et al. propose an energy-aware UMTS deployment which dynamically shuts down sites from a single operator, but meets performance requirements by capitalizing on diurnal use patterns [24]. Their approach is complementary to the one introduced by this paper. Simple simulation results indicate significant gains, but the authors do not seem to account for the impact of applications, such as P2P. As mobile WMAN operators offer inexpensive data bundles, users should be expected to exhibit a different behavior during the night than what is common in UMTS networks today.

The proof-of-concept simulation results indicate that an information-centric approach, based on self-certifying objects, may be instrumental in reducing the energy use of future WMANs, and ICT in general. That said, our simulation framework needs to be further enhanced with several detail levels. The scenario of Section III, for example, is modeled at a high level, partly due to the state of definition of NetInf components and partly because no suitable packet-level simulator is available at this time. Besides, this scenario considered only video streaming. We are in the process of enhancing the level of detail and introducing a services model to obtain more accurate results. Moreover, we plan to evaluate the potential gains in a large simulation scenario such as the city-wide Wi-Fi deployments discussed in §II-A. Nonetheless, the preliminary results presented in this paper are promising.

V. Conclusion

This paper argued that developments in network access and application use point towards the need for adopting a multiaccess information-centric approach for the Future Internet due to one more reason: energy consumption. ICT energy consumption has been on the rise, and as broadband WLANs and WMANs reach even more people, the energy consumed can be expected to increase dramatically. The current host-centric approach does not seem well-suited for addressing the new needs arising. Taking energy consumption as a core metric of performance from the design phase of a multiaccess network of information may prove fundamental in designing a “greener” Future Internet. The simulation results indicate that WMANs which are operated as “walled gardens” are more energy consuming due to their reliance on overprovisioning to achieve performance and coverage targets. In contrast, a cooperative multiaccess NetInf maintained the same overall power consumption envelope serving twice as many nodes.

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