Energy-Efficient Wireless Mesh Infrastructures

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***Abstract*—The Internet comprises access segments with wired and wireless technologies. In the future, we can expect Wireless Mesh Infrastructures (WMIs) to proliferate in this context. Due to the relatively low energy efficiency of wireless transmission, as compared to wired transmission, energy consumption of WMIs can represent a significant part of the energy consumption of the Internet as a whole. We explore different approaches to reduce energy consumption in WMIs, taking into account the heterogeneity of the technologies and the interaction with wired networks. Finally, we present an example scenario where the application of these methods is discussed.**

I. Introduction and Concepts

Internet traffic is steadily growing due to the increasing number of users and the higher service demands. At the same time, energy consumption has become a key social and political issue. Therefore, the energy consumption of the Internet might represent a fundamental constraint for its future growth.

The Internet comprises three segments: the core, metropolitan/edge, and access segments. The core network comprises large routers, linked with high-capacity Wavelength-Division Multiplexing (WDM) optical fibres. The metropolitan segment constitutes the bridge between the access network and the core network; it is connected to the core network via several edge routers and it contains several edge nodes connected to the access network. Currently, this segment comprises electronic switches, but there is very active research on optical networking solutions such as Optical Burst Switching (OBS) or Optical Packet Switching (OPS). The access network connects user terminals with the edge node. Multiple technologies are employed nowadays and this can be expected to be the scenario in years to come. The Digital Subscriber Line (DSL) technology is gradually being replaced by optical fibre. Although in some cases DSL is replaced partially, forming what is called Fibre-to-the-Node (FTTN), the general evolution is towards Point-to-Point (PtP) optical fibre or the more economical and robust Passive Optical Network (PON) technology, as shown in Fig. 1. In PON, an Optical Line Terminal (OLT) is located at the local exchange and is connected to several Optical Network Units (ONUs). Each ONU is linked to the OLT through a different fibre, but the fibres are joined together by a passive splitter into a common fibre to the OLT.

Recent developments in wireless technologies have made them attractive as part of the access segment of the Internet. The main attractiveness of wireless technology for the access results from its flexibility, permitting in most cases terminal mobility and saving on infrastructure for the operator. On the one hand, cellular systems have evolved towards more efficient data transmission, and today can be useful for some data services. On the other hand, IEEE 802.11 (WiFi) technology has become widespread and its maximum link capacity matches that of some wired technologies. Additionally, new technologies have become available, such as IEEE 802.16 (WiMAX), with Base Station (BS) capacities close to those of ONUs.

The wired and the wireless technologies in the access segment can be combined in order to increase resource utilization efficiency while satisfying the user's demands. We expect future access networks where ONUs are integrated with WiMAX BSs, WiFi Access Points (APs), or new-generation cellular BSs. These wireless nodes could be connected to form a Wireless Mesh Infrastructure (WMI), as shown in Fig. 1. The WMI is formed by a set of static, wireless devices, which we call Wireless Mesh Nodes (WMNs). User terminals, which can be either static, nomadic or mobile, connect to a WMN via one wireless hop, thereby alleviating the complexity of multihop wireless routes involving several mobile devices and relieving the user terminals from forwarding third-party packets. WMNs route and forward packets between different user terminals or between these and the wired access segment, with the ability of using several wireless hops if needed. WMNs may have multiple interfaces. We can expect WMIs to become widespread in future access networks, since they are easier and more economical to deploy than fibre, they provide a more pervasive connectivity as compared to wired access, they have higher flexibility than homogeneous access infrastructures, and they enjoy lower complexity and increased resource efficiency as compared to Mobile Ad hoc NETworks (MANETs).

Despite the mentioned advantages of WMIs, in the next section we will see that the energy efficiency of wireless

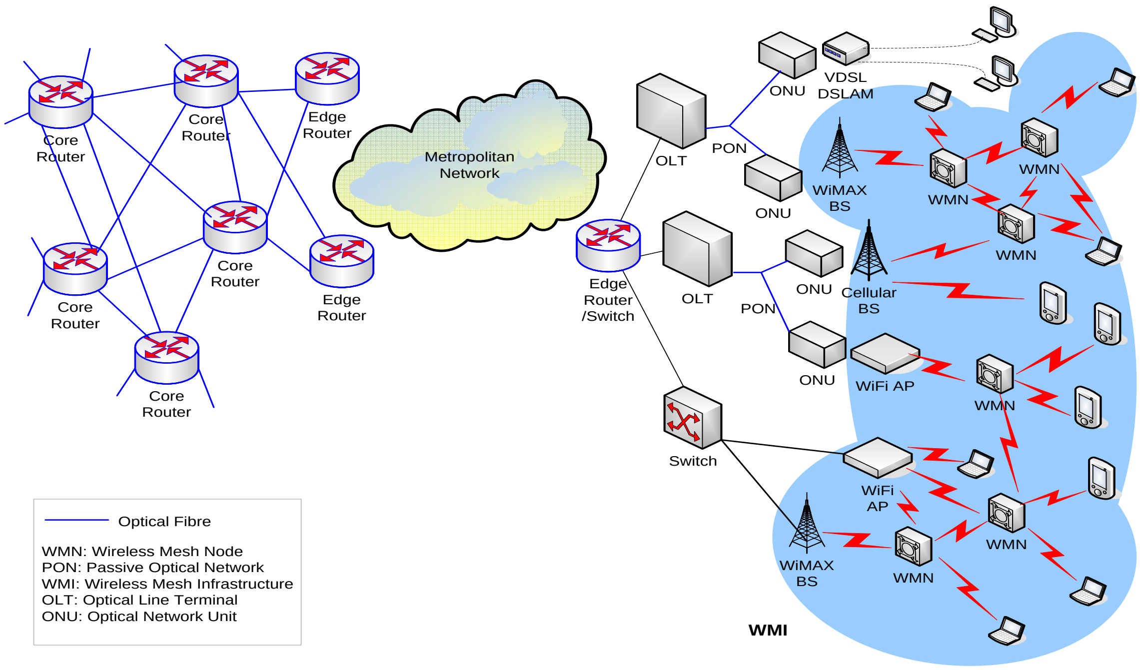

Fig. 1. General view of the Internet.

transmission is relatively low. This implies that the energy consumption of WMIs have a severe impact on the overall energy consumption of the Internet, mainly if we consider the expected proliferation of WMIs in the access segment. Although there has been a lot of research on energy issues in wireless sensor networks and MANETs, the main issue there is saving energy to prevent node batteries from being depleted. In contrast, WMNs will be easily supplied with energy and the issue is to reduce the energy consumption as a whole. This work addresses the relevance of the energy consumption in WMIs, presents several methods to reduce energy consumption that partly exploit the heterogeneity of the access network, and discusses the application of these methods in an example scenario.

II. Energy Consumption of Considered Networking Technologies

The heterogeneity of the Internet is essential for the analysis of the weight of the different segments in the overall energy consumption. In this section we analyze and compare the energy consumption characteristics of the different considered technologies.

A. Network Backbone and Wired Access

Recent studies [2] show that the power per user required by the core routers, together with the core links and the metro segment, is below the power per user consumed by either ADSL, FTTN, PtP fibre, or PON, provided that the average access rate per user is below 40 Mbit/s and that the over-subscription factor (the ratio between user peak rate and average peak rate) is at least 10 (which is an ordinary value). At an average user rate of 16 Mbit/s, the energy needed in the aggregation of the core and metro segments can be expected to be below 0.3 μJ/bit. The consumption of the wired access segment under these conditions is 0.4 μJ/bit in the case of PON, and 0.6 μJ/bit in the case of PtP. In addition, upcoming optical bypass techniques can reduce the core router consumption by a factor of about 50% and, in the metropolitan segment, OBS and OPS technologies could be improved in the future to provide energy savings as compared with electronic routers.

B. WiMAX

Comparative energy consumption data of WiMAX, and several wire/optical based access technologies in [3] show that WiMAX has the highest energy consumption per data unit. The difference is especially visible for high data rates where the energy consumption per data unit with WiMAX decreases very slowly while the other technologies are significantly more efficient. The authors in [3] use a simple model where the external power supply and cooling account for half of the energy consumed by the user modem, and the Customer Premises Equipment (CPE). For average access rates per user of 2.5 Mbit/s, the energy per bit in WiMAX is 10 μJ, slightly larger than that of PtP fibre or PON; however, for average access rates of 16 Mbit/s, WiMAX consumption barely improves, so it becomes more than one order of magnitude larger than that of PON and PtP, as was mentioned in the previous subsection.

C. Consumption of Cellular Access Networks and Devices

In mobile cellular networks, the overall consumption of user terminals is rather small, accounting to less than 10% of the total network consumption. Indeed, since mobile terminals rely on batteries, they were already designed to be power-efficient. The network infrastructure, on the contrary, has typically been designed with targets expressed in terms of radio coverage, capacity and other service requirements, but not energy consumption. According to recent estimates, the cost of the energy needed to run the infrastructure can reach 50% of the operational expenditures (OPEX) of operators [5]. About 80% of this cost is due to the access segment that comprises the BSs [7]. Indeed, while the individual BS consumes from less than 1 KW to about 2 KW (with lower values for 3G networks with respect to 2G networks), the extremely large number of these devices makes the access segment far the most demanding. It is estimated that the total number of BSs in the world accounts for a total consumption of about 25 MWh per year. The transmission power represents only a few tens of Watt. Mobile devices of 3G networks show an energy efficiency fingerprint of an average upload/download of about 12.5 to 24.6 μJ/bit [10].

The situation is going to worsen, due to the need for high data rates that will lead to denser access networks. To reduce consumption different approaches are taken. From one side, new hardware solutions and transmission technologies are under investigation to improve efficiency of the devices; from the other side, solutions based on different planning strategies and on the use of sleep modes are being considered.

D. Energy Consumption of Short-Range Wireless Networking Technologies and Devices

An increasing number of modern mobile devices are equipped with multiple wireless access technologies. Besides the already mentioned cellular systems (3G, GSM) and WiMAX, we often find IEEE 802.11 (WiFi) and Bluetooth interfaces. Each technology has different characteristics with respect to transmission range, throughput and energy consumption, which are closely connected. Results show that WiFi, as the most important technology in WMIs, requires significantly less energy than 3G [1]. In idle state, WiFi consumes orders of magnitude more energy than 3G (both in normal and in power saving mode), but the worse overall performance of 3G can be explained by the standard's inactivity timer behaviour. Depending on the amount of data to transmit the radio either switches into a high power mode which reserves a complete channel, or into a channel sharing state which requires about half the energy of the high power mode. After data transmission the radio is not immediately set to idle state, but remains active until an inactivity timer expires, which has the advantage that in case of new data the channel reservation overhead is reduced. For WiFi there is little difference between up- and download energy consumption, while, on the contrary, measurements in [10] show that 3G data upload requires approximately twice the energy of a download of the same size. An IEEE 802.11b/a/g transceiver requires approximately 0.1-0.2 μJ/bit when working in transmission mode constantly; in reception mode, this becomes a 30% smaller. An upcoming amendment, IEEE 802.11s, focuses on the use of IEEE 802.11 technology to form WMIs. Part of their work contains proposals on power saving. The underlying idea is to let some nodes buffer frames to other nodes, so that they are transmitted only at negotiated times. This way, the destination nodes will be able to save some energy.

III. Assuring Energy Efficiency in WMI

WMIs are very flexible since they can change their structures and resource distributions easily while maintaining the required service. Specifically, the mesh topology allows to select connectivity options as demanded, the presence of multiple wireless interfaces at clients allows to connect via different wireless technologies, and the wireless medium itself allows to adapt data rates and transmission ranges. This flexibility supports that energy efficiency in WMIs can be significantly improved. Besides the trade off between energy consumption and service quality, we need (i) methods enabling flexible, energy-aware adaptation control and (ii) methods that inherently reduce energy consumption. Hereby, the solutions can be either local solutions targeting one single entity in the WMI or distributed requiring coordination between multiple entities.

A. Energy-aware WMI Adaptation

Energy-awareness describes the possibility of systems to "know" about energy consumption, which enables adaptations during runtime. One prerequisite is the ability to monitor, measure, and estimate energy consumption of network components. For example, network interfaces operated under various modes and the overall energy consumption of a network node are of interest. Focusing on adaptation, hardware-based methods, software-based methods, and enablers for resource consolidation are addressed.

Most modern hardware devices are energy-manageable. More and more wireless routers and smart end devices allow also to monitor energy consumption and to adapt operation. Wireless stations can be switched between active and power saving modes, like in IEEE 802.11, and transmission ranges and rates can be adapted.

In addition to hardware techniques, software techniques support flexible reaction to changing energy states and service demands. Several methods can be implemented and combined based on the service quality that should be provided while working energy-efficiently. The software techniques range from architectural decisions such as cross-layer approaches to on-demand compensation techniques. Cross-layer design allows for optimizing in terms of less energy consumption while considering multiple communication layers. On-demand compensation techniques aim at providing the required quality of service by invoking sophisticated means. For example, in case of powering down a number of mesh routers, higher bit error rates and packet losses are expected; by including Forward Error Correction (FEC) on the application layer, the quality can be maintained while still saving significant amounts of energy.

The concept of network virtualization, which is the abstraction of physical networks, is used in a way that makes new managing strategies possible by either splitting or aggregating the physical resources. One physical resource can be splitted and thus shared by multiple virtual networks, while several physical resources can be aggregated to one virtual network (e.g., multi-homed device receiving data streams via two physical channels that are multiplexed on the application layer). Network virtualization is based on virtualized network devices and virtualized Network Interface Cards (NICs). Such a device can implement multi-homing by using one of its virtual interfaces to create, e.g., an ad hoc network with other stations while keeping its connection to the infrastructure AP using another virtual interface. Another use case for virtualization is easy migration of network services supporting consolidation and, finally, switching off network resources while others take over.

B. Reducing Energy Consumption and Increasing Energy Efficiency in WMIs

There are several parameters that have an effect on the energy consumption of WMIs. The major ones are:

- the number of APs, BSs, or mesh routers covering a particular area,
- the distance between them and their transmission power,
- the environment, which affects the propagation characteristics,
- the traffic load, and
- the number of wireless user terminals in the covered area.

Some of these parameters change dynamically out of control by the network management (e.g., number of active stations), while other manageable parameters can be manipulated to gain the maximum of energy saving.

Methods for reducing energy consumption in WMIs can be distinguished between *local* and *distributed* methods. Local methods consider only a few parameters and are dedicated to single devices, while distributed methods consider solutions involving several nodes, coordination among those nodes, and feedback loops. The concepts range from simply switching local resources on/off (e.g., links, nodes, interfaces) to implementing a distributed, energy-efficient algorithm in the network considering, e.g., combined techniques and migration of virtual interfaces and feedback loops.

Main local energy reduction concepts are

- **Switching network interfaces on/off.** Let us take the example of WiFi. In this technology, two types of power management modes are defined. A wireless station can operate either in active mode or in power saving mode. In the active mode a station is fully powered, while in power saving mode a station can be in one of two different power states, either in awaken state or sleep state. In power saving mode, if the traffic destined to the station is low, the station can turn into sleep state. Network virtualization techniques can be used to share NICs, thereby saving the power for another physical card.
- **Adapting transmission ranges, modulation formats and coding schemes.** By regulating transmission power, the transmission range can be altered at the wireless interface to change between different power-intensive operation modes. Unfortunately, when wireless multihop communication is considered, the presence of diverse transmission ranges can have an adverse impact on the Medium Access Control, since more hidden nodes will result in general. Still, transmission power can be regulated uniformly among the WMI nodes, although this will require a careful analysis of the trade-off between network connectivity and spatial reuse and should obviously be performed in a distributed manner, rather than locally.
  The adaptation of modulation formats and coding schemes is very useful, since it can compensate for dynamic channel fading, and it can enhance retransmission efficiency. In a wireless multihop network, however, it is necessary to have additional co-ordination means between neighbouring nodes. Although some promising ideas to support routing failures, such as overhearing transmissions of nearby nodes, may become more complex to design, the advantages of modulation format and coding are strong.
- **Select wireless links consuming less energy.** In case of multi-homed devices, devices can select the least power consuming alternative for communication (if it still provides sufficient quality).

These basic local methods can be applied to the distributed system of nodes operating energy efficiently, hence, becoming *distributed solutions*, i.e., the nodes have to reach a (simple) consensus in order to implement these methods.

The network is usually planned and dimensioned taking into account two needs: (i) provide a given QoS target under peak hour traffic and (ii) provide service continuity and full radio coverage over the whole area of interest. The joint satisfaction of these two constraints can make the network over-dimensioned in times of low demand. In addition, the duration of off-peak periods can be quite large leading to long over-dimensioned periods. Thus, since network energy consumption is directly related to the amount of deployed capacity (i.e., the number of active devices), the network consumes much more than what is strictly needed.

Most of the solutions for improving the energy efficiency of WMIs rely therefore on some form of adaptation of the capacity to the actual needs of the users. These solutions can be distinguished into methods that provide full coverage and methods that provide only partial coverage.

Methods that provide full coverage adapt capacity to the actual needs of the users but always guarantee full radio coverage. Possible methods are:

- **Adapting the capacity by switching on and off the devices.** The switching scheme aims at powering on the minimum number of devices (or the combination of devices that consume the least energy) that can *jointly* provide full coverage and enough capacity. Basically, this corresponds to having a minimum set of devices that provide coverage and an additional set of devices that are powered on to provide additional capacity when needed. Resource sharing, e.g., by virtualizing NICs as presented in our previous work [6], falls in this category of methods. By consolidating hardware, some hardware can be put in low-power mode and energy consumption can be reduced, saving the difference in energy consumption per low-power node when compared to an active node and adding the amount of energy consumed by hosting more networking processes just on fewer network nodes. Depending on the type of device, different amounts can be saved.

- **Decreasing the number of active devices by increasing the transmission power.** These solutions act on the transmission power of the active devices to increase coverage and make it possible to switch off some devices that are not strictly necessary for capacity purposes. Here, the energy consumed for increased transmission power has to be rated against the power consumed by additional active devices. Given the energy consumption characteristics of the different wireless technologies considered, it is expected that the amount of energy that can be saved by switching off wireless devices is still significantly more than the overhead in energy consumption that results from increasing the transmission power of the remaining nodes even under high traffic loads.
- **Decreasing the number of active devices by introducing compensation methods for service degradation.** When switching off devices, the error rate is likely to increase and the throughput is likely to decrease. Compensating mechanisms can be introduced to react to these degradations. Forward Error Correction (FEC) is a means to achieve this aim. The cost of sending more data is related to the increase in quality or/and to the situation where all mesh routers are active (i.e., consuming more energy). Besides, FEC causes additional processing overhead which should not be ignored (see, e.g. [8]).

Methods that relax the assumption of full coverage are feasible when the traffic reaches very low values either in time (at off-peak hour) or in space (in some geographical locations). They adapt capacity to the actual user needs and may give up full coverage. This higher degree of freedom comes at the cost of some possible service discontinuity or QoS deterioration. Under these demanding circumstances, additional methods are applicable:

- **Relaying of messages by ad hoc networking to increase coverage.** Some devices, chosen between the least critical and mostly under-utilized, are switched off. Their role in providing radio coverage is substituted by ad hoc networking, exploiting the cooperation of users. User terminals (stations) which are a part of a wireless cell covered by an AP can extend the coverage area by creating ad hoc networks with those located in uncovered areas, and thus, can relay traffic between the AP and these stations. We are referring to such stations as relay stations. This can be achieved by equipping relay stations with multiple NICs or, instead, a virtualized NIC to save energy. In this case, some QoS deterioration is likely to appear in terms of additional delay and/or lower capacity. While these schemes basically avoid service discontinuities, some energy cost is demanded to user terminals when operating as relays. Energy is saved by shutting down some APs, but on the other hand, extra energy is consumed by the relay stations. This is due to the energy consumed for relaying the traffic from and to stations connected with the relays in ad hoc networks. But since such relay stations are always active, the energy consumed for extra transmitting and receiving of traffic for others does not add that much; according to the numbers given in [9], a WiFi station consumes around 0.9 W (idle), 2.0 W (transmitting), and 1.2 W (receiving). When comparing these values to the energy consumption of an AP, which consumes up to 20 W (e.g. Cisco Aironet 1250 Series AP), it becomes clear that switching off an AP implies much more energy saving potential than overhead is generated on the relays.
- **Including Delay/Disruption Tolerant Networking (DTN).** A complementary approach to relaying in ad-hoc manner is the DTN (Delay/Disruptive Tolerant Networking) paradigm which suggests itself as a promising solution to intermittently connected nodes, where a sub-set of nodes (the so-called custodian nodes) can temporarily buffer the data intended for a node in case there is no path towards the recipient. Such an approach may compensate the disruptions and greatly improve the performance of applications tolerant to delays. In our context, we argue that the application of DTN principles is very promising, since energy per bit in the wired access segment is much lower than that of wireless technologies. DTN bundles can be stored in different nodes of the EPON, either ONUs or OLTs. In Fig. 2 we find an example of what occurs when an end user terminal that is receiving data changes its point of attachment: instead of sending the data to the recipient via several hops in the WMI, the necessary DTN bundles can be received from the closest active custodian ONU. This solution requires the optical nodes to inter-operate with the mesh network, to perform effective routing of DTN bundles and to implement a suitable bundle storage management. Having in mind that the PON uses a centralized MAC mechanism, and that service demands for the downstream direction have negligible impact on resource utilization in the upstream direction, if we store DTN bundles in the OLTs, the corresponding bundle routing scheme for downstream data will become trivial within the scope of a single PON.
- **Detecting the presence of devices, traffic and on-demand powering schemes.** Techniques to detect the presence of traffic and other devices are implemented to wake up stations only if necessary. Hence, the QoS deterioration is reduced at maximum but the occurrence of some service discontinuity or delay in accessing the

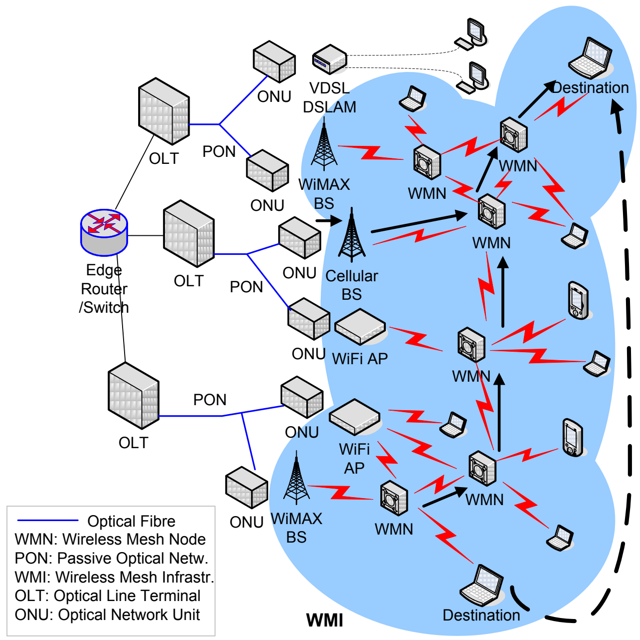

Fig. 2. An example of the application of DTN concepts.

service is still possible. Here, the energy consumption caused by detecting devices around has to be added to the overall energy consumption and related to the energy saving by powering down devices.

While the described methods concentrate mainly on separated communication layers, optimizing for energy efficiency is expected to achieve better results when multiple layers interact following, thus, a *cross-layer* design approach. While on the physical layer, major concerns are adapting modulation, coding, or transmission power (and, therefore, transmission range), on the data link layer, medium access control includes the handling of periods of inactivity (on/off cycles of NICs and inactive nodes for saving energy). On the network layer, routing decisions are taken, i.e., selecting the best route according to an energy efficiency metric such as energy consumed per bit e [J/bit]. To enable taking the right routing decision, at least the information on energy efficiency of links (taking into account the results of the methods of the lower layers) are required. Additionally, cross-layer methods may combine methods such as adapting transmission range and retransmission rate based on one utility function for energy efficiency, since these two mechanisms depend upon each other, i.e., in case of low power channels the retransmission rate is likely to increase. The disadvantages of cross-layer energy efficiency methods are due to the increased complexity of the optimization function and the impact they may have on maintaining a modular, open network design.

C. Reactive and Pro-active Implementations

The choice of the energy efficiency method is based on the constraints for the service provisioning combined with the traffic pattern (for example, if traffic is never that low, on-demand powering schemes are probably unfeasible). Given these categories, there are different ways of implementing the methods, based on how decisions are taken, either in (i) *reactive* manner, based on traffic measurement and detection, or in (ii) *proactive* manner, based on the presence of mobile devices and load prediction.

Reactive implementations adapt to currently observed situations, which means that they are always "one step behind". Basically, all mentioned methods can be applied in a reactive manner if the adaptations can be finished in time. If not, proactive implementations might be more adequate.

Proactive implementations involve the invocation of mechanisms fitting to a situation before the situation occurs. This implies that it is feasible to invoke the mechanism in advance. For example, if a mobile device changes from one AP to another, resource reservation and slot/channel assignment can be carried out before the mobile device actually changes AP while some synchronization tasks between an AP and the mobile device require interactions and cannot be carried out in advance. A typical example are releases of resources in hotspot areas, which should not be done before a mobile station moves out of the area.

The main advantage of proactive implementations is the reduction of delay while the main disadvantage is the possible wrong invocation of mechanisms. Proactive implementations often rely on a model of the likelihood of future situations, i.e., a prediction component. The improvements gained from proactive implementations rely strongly on the accuracy of the predictor.

In future heterogeneous networks, nodes are expected to be dynamic in terms of mobility and load generation. To react to these dynamics in time, the following prediction types are considered:

- **Mobility prediction.** In case the movement of devices shows regularities and can be captured in mobility models, it is possible to forecast future movement characteristics. Individual mobility can be considered as *micro mobility*, i.e., describing single movements. Mobility prediction can also be used to describe *macro mobility*, such as the distribution of nodes in areas. By targeting micro mobility, the energy consumption of the predictor has to be considered and compared to the amount of energy saved to provide effective mechanisms, as presented in [4]. The saved energy always has to be higher than the energy needed to execute the prediction algorithm.
- **Load prediction.** Although load is related to user mobility, it extends mobility prediction by including also the traffic expected to be generated. Here, daytime patterns are modeled, such as day/night or rush hours. For example, it is expected that less resources are required and can be switched off when fewer nodes are dwelling as stations in the access network. However, if mobile stations are forming an ad-hoc network, this rule may change and optimization will have to consider also the density required to provide adequate connectivity.

IV. USE CASE WMI SCENARIOS

In this section we consider a possible scenario in which some of the solutions for energy efficiency, that are described in the previous section, are applied.

Consider a street, in which the radio coverage is obtained through a simple BS layout, such as the one shown in Fig. 3(a). Given the daily traffic pattern, there are long periods of low traffic in which the deployed capacity is much larger than what is strictly needed and this translates into a considerable energy waste. Thus, during low traffic periods, some BSs are switched off to save energy, according to one of the schemes presented in previous sections.

Case 1. Transmission power increase.

When some BSs are switched off, those that remain active increase their transmission power so as to provide radio coverage over the area of the BSs that are off. Full coverage is guaranteed. This scheme is sketched in Fig. 3(b). Assuming that all the BSs are similar and consume about the same power, and given also that the transmission power is a marginal portion of the actual BS energy consumption, the saving is simply given by the fraction of BSs that are switched off.

The main limitations of this approach are related to signal propagation issues. The actual extension of the radio coverage depends on the characteristics of the propagation channel, which, in turn, depend on the physical and environmental conditions. Moreover, transmission power should not exceed the limits imposed by law to reduce electromagnetic pollution.

Case 2. Ad hoc networking.

When some BSs are switched off, connectivity in the shadowed areas is provided by ad hoc networking. Vehicles that need connectivity contact other vehicles that are close to them and look, in an ad hoc fashion, for a path that connects them to a BS that is still active, see Fig. 3(c). To be feasible, this scheme requires from the user side, that terminals are willing to cooperate and that they can work in ad hoc mode. Also, vehicle density should be large enough to make the ad hoc network (almost) fully connected. The ad hoc path should be one or two hops at most also to preserve other QoS parameters, such as access delay and throughput.

Case 3. A DTN approach.

Whenever a DTN approach is viable, i.e., when the provided services are delay tolerant and QoS constraints are loose, the system might give up full coverage. In this case, the system provides service only through the BSs that remain on. Once a vehicle is in contact with an active BS, it starts a service, e.g. a connection to retrieve some kind of data. Whenever the vehicle enters a shadow region, data directed to the vehicle is stored in the following BS that the vehicle should approach, see Fig. 3(d). Mobility prediction methods are needed here.

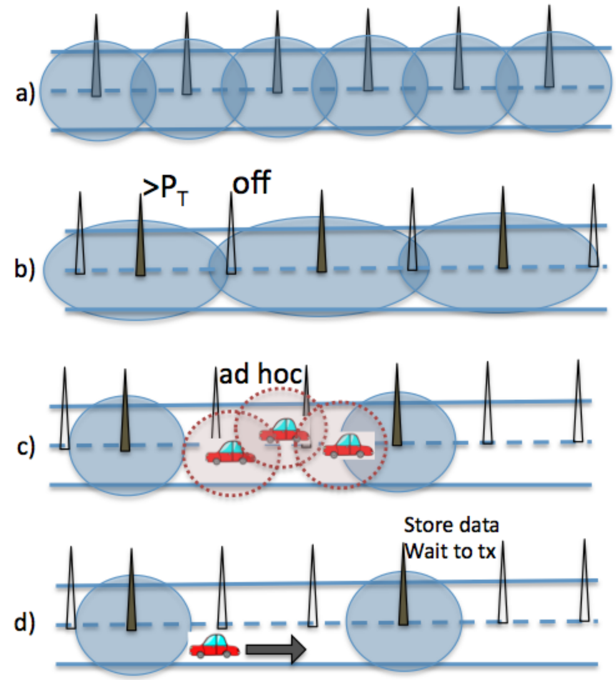

Fig. 3. Use case: the vehicular scenario. All BSs are on (a), EE with increase transmission power (b), EE with ad hoc networking (c), EE with DTN approach (d).

TABLE I
COMPARISON BETWEEN SCHEMES IN THE VEHICULAR CASE

Scheme	Coverage	Constraints	Saving	Services
Tx power	full	propagation	medium	all
Ad hoc	full	veh. density	medium	low bandwidth
DTN	partial	QoS	high	delay tolerant

Table I summarizes the main characteristics of the proposed solutions for the considered scenario. Besides the possibility to provide full coverage, the table reports a few other aspects. The most critical constraints on the applicability of the solution are related to propagation issues in the case of increased transmission power, to the vehicle density in the ad hoc method, and to the QoS constraints in the DTN approach. The potential saving, which for all the considered solutions is given by the fraction of BSs that are switched off, can be very large with the DTN approach, depending on how much delay one is willing to allow in favor of energy saving. Finally, the table reports also the kind of services that are suitable for the solution. The ad hoc case might be reserved to services that require a relatively limited amount of bandwidth.

V. CONCLUSIONS

Energy consumption of WMIs can represent a significant part of the energy consumption of the Internet as a whole due to the intrinsic power inefficiency of wireless transmission as compared to wired links and the relatively large number of devices. However, the extraordinary flexibility of WMIs in terms of topology and multiplicity of interfaces, provides large potentials for reducing this important parameter. Different approaches are useful for this purpose, such as application layer FEC or virtualization of NICs –turning off NICs or selecting efficient links. Also, methods can resort to a relaxed assumption of full coverage, which rely on ad hoc networking and DTN principles (specially useful in the case of heterogeneous wired-wireless access networks). Energy saving methods can be implemented in a reactive way (which is relatively simple) or in a proactive manner (which can have better performance). Cross-layer approaches have a high energy-saving potential but, when applied, they should maintain a modular, open network structure. In general, methods for improving energy efficiency need to be applied having in mind the different technologies involved, the presence of distributed mechanisms and the different communication layers involved.

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