Wireless Backhauling for Energy Harvesting Ultra-Dense Networks

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***Abstract*—Due to a non-negligible amount of energy consumption of state-of-the-art small cells at idle mode, energy efficiency of network decreases with densification. Therefore, energy efficiency in ultra-dense networks (UDNs) is one of the key challenges for mobile network operators (MNOs) to reduce their operative expenditure (OPEX), and to mitigate the carbon footprint. Low-power and low-cost dense networks are vital to extend next generation cellular networks functionalities by improving network capacity in hot-spot areas, and to deploy networks in short time periods. In energy harvesting networks, access points (APs) may perform both backhaul and access data communication, simultaneously; removing UDN dependency on optical distribution network and electrical grid. In this paper, different power modes and essential signaling for operation of such APs are introduced, aiming to reduce energy consumption of UDNs by integrating energy harvesters into APs, equipped with wireless backhaul.**

***Index Terms*—energy efficiency, energy harvesting, backhaul, UDN.**

I. INTRODUCTION

To meet the high traffic demands in areas like airports and large shopping malls for both outdoor and indoor deployments, several studies indicate to increase the capacity of both access and backhaul networks. For wireless access networks, one promising solution is to use an UDN deployment, which can be realized with sites with sites placed within 10-50 m of each other [1]. By 2030, it is expected that UDNs to be covering most urban indoor and outdoor areas providing cell-edge data rates of 100 Mbps to user equipments (UEs) [1], [2].

When deploying UDNs, MNOs face key challenges that must be addressed to satisfy subscribers growing traffic demand, while also minimizing the OPEX and capital expenditure (CAPEX). For example, site costs can be minimized by deploying compact and lightweight APs that are simple to install and remain discreet, and by choosing the suitable backhaul option. Deployment of the backhaul through fiber links may increase the CAPEX. Moreover, the cost of power wiring per AP can grow, and consequently increase the CAPEX even further.

In addition, from power consumption point of view, wireless access network is responsible for up to 60%-80% of the telecoms total energy consumption [3], which corresponds to about 40% of the total OPEX [4]. Further, recent surveys show that 96% of MNOs consider backhaul as one of the most important challenges to small cell deployments, and this issue is more severe in UDNs [5].

Millimeter wave communication has provided new opportunities and has been proposed to support high bandwidth demand (up to 400 MHz) in 5G cellular networks [6]. For this reason, millimeter wave communication is one of the potential candidates for high bandwidth backhaul connection of UDNs, at cost of increase in energy consumption. Other wireless backhaul technologies include two-way relaying [7]. However, such a solution may not scale for UDNs, therefore, their usage is limited for UDNs [2].

In this work, energy-harvesting APs with wireless backhaul, refer to as autonomous-APs (A-APs), are studied, and network architecture and corresponding signaling are proposed. Furthermore, the advent of A-APs removes the rigidity of traditional UDNs which are tightly coupled to the wired power and fiber links. Moreover, A-APs enable fast and efficient capacity and coverage improvements with minimum network planning and deployment costs. A-AP has highly potential to reduce both OPEX and CAPEX, while maintaining user quality of experience.

The energy consumption of the wireless backhauling can be higher compared to the fiber link [2], [8]. Therefore, energy efficiency of A-APs is paramount for network operation, without sacrificing users quality of experience. Authors in [9], investigated the impact of backhaul on the energy consumption of wireless access networks, taking into consideration different data traffic requirements. According to their findings, backhaul can potentially become an issue in UDNs.

Moreover, authors in [10], the backhaul and radio access are optimized jointly, and it is introduced as a key enabler to next generation mobile networks; the possibility of optimizing the energy consumption, in addition to network and users performance, is also validated.

In this work, in order to operate the network off grid, the essential signaling such as switch on/off commands, energy and traffic state reports from A-APs to M-APs are introduced. The available harvested energy and traffic information is combined at the M-AP as a central node in order to provide better radio resource management for the backhaul link in respect to latency, throughput and energy efficiency.

This paper is organized as follows. Section II describes and reviews the background of energy harvesting APs, briefly. The proposed A-APs different power modes and signaling are explained in Section III. Traffic load and power usage control are utilized as effective way to adjust the users traffic demand to available energy in Sections IV and V, respectively. These are followed by conclusion in Section VI.

II. BACKGROUND REVIEW

Energy harvesting APs scavenge energy for their operation (both backhaul and radio access) from solar panels or wind turbines. The harvested energy is stored for the later use when is required. The amount of harvested energy depends on the intensity of the received sun radiation or wind speed at the target AP location and time of day.

Similarly, the capacity requirements of the cellular network varies over time; reaching to maximum during the peak hours, and in its minimum during the low traffic periods [11]. The mobile network can be configured to have its maximum active AP density during the peak hours, while during the low traffic periods the majority of the APs can be switched off to save energy, except those APs responsible for coverage purposes. We refer to main APs that inevitably require fiber backhaul and grid power as master-APs (M-AP). M-AP can be configured to provide backhaul connectivity for one or multiple A-APs. In other words, A-APs need to be under coverage of at least one M-AP. Additionally, M-APs can serve UEs, while serving A-APs.

Fig. 1 illustrates the basic schematics of A-AP, which is comprised of energy subsystem (ESS), backhaul transceiver (BH-TRx) and the access transceiver (AC-TRx). ESS has energy harvester (either solar panel or wind turbine or both), battery and power management system, which can divert the energy flow from battery to BH-TRx or AC-TRx or can switch off the entire communication system. Similar to A-AP, M-AP has a similar set of components, without ESS.

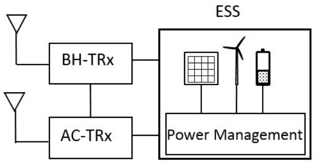


Fig. 1. A-AP with separated transceivers for backhaul and radio access.

Fig. 2 depicts the wireless links between UE, A-AP and M-AP. UE can be connected to the network either through A-AP access link or M-AP access link or both. In this work, for simplicity, we consider only the case that UE does not have dual connectivity, and is connected one AP at time.

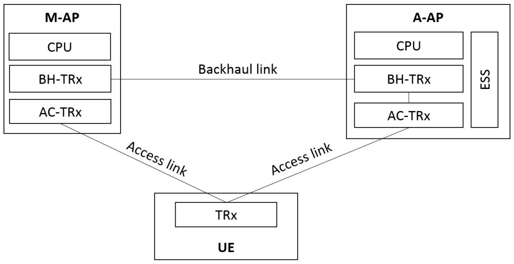


Fig. 2. The wireless links between M-AP, A-AP and UE.

III. THE PROPOSED PROTOCOL ARCHITECTURE

In the proposed protocol architecture, A-APs have three main operating modes, *sleep mode*, *idle mode* and *connected mode*. In *sleep mode*, A-AP consumes minimum amount of energy, and does not have any access or backhaul connectivity. During the *idle mode*, A-AP can report its energy state information (ESI) to M-AP through backhaul link, and also is able to transmit and receive radio access control signaling as well as broadcast signaling. Furthermore, *idle mode* enables stable and smooth transition between the energy-efficient *sleep mode* and high-energy profile *connected mode*.

In order to adjust the network to the traffic demand and energy arrival, *idle mode* is categorized to energy-aware idle mode, and traffic-and energy-aware idle mode, referred to as *idle-1* and *idle-2* modes, respectively. *Idle-1* and *idle-2* modes differ in their functional and power consumption profiles. Similarly, *connected mode* is divided into two modes, *full connected mode* and *energy preserving mode*. In *full connected mode*, the energy consumption rate is higher than the energy harvesting rate, resulting in discharging the battery, and A-AP enables very high data-rate communication between associated M-AP and UEs. However, in *energy-preserving mode*, the harvester generates more than energy required for operation of A-AP, hence the surplus energy charges the battery. Moreover, in *energy-preserving mode*, M-AP manages A-AP's operation and load, and hence the energy utilization is maintained within a safe range.

Fig. 3 illustrates aforementioned power modes and the possible transitions between them.

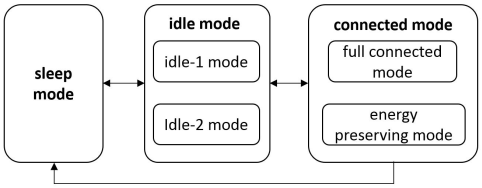


Fig. 3. Power modes and transitions between them.

A. sleep mode

During *sleep mode*, both BH-TRx and AC-TRx are inactive. *Sleep mode* takes place during low energy arrival periods and/or low traffic periods. During *sleep-mode*, the ESS measures the energy harvesting intensity and battery charging levels, continuously.

B. idle-1

During *idle-1* mode, backhaul link operates according to pre-signaled discontinuous reception (DRX) pattern, and A-AP can report its ESI (i.e. battery charging levels, energy harvesting intensity and power consumption information) to network. Accordingly, M-AP may reconfigure DRX or send new controlling data including the state change commands to the A-AP. In order to improve the energy efficiency and the availability of the A-AP operation, the DRX cycle can be dependent on the current energy state. During *idle-1* mode, the AC-TRx is inactive.

Fig. 4 illustrates the essential signaling between M-AP and A-AP during *idle-1* mode. In the connection set-up phase, M-AP sends the initial DRX parameters to the A-AP after which the A-AP starts sending ESI to M-AP following the DRX configuration. The A-AP periodically switches on, synchronizes to M-AP, and sends ESI to M-AP, and then switches itself off. M-AP reads ESI and compares the battery level of the A-AP (E) to the pre-configured threshold (T_{E1}). If the energy is below the threshold, the M-AP sends a switch-off command, once A-AP receives the switch-off command, it enters to *sleep-mode*. Otherwise, M-AP calculates new DRX parameters, which are selected based on the energy saving requirements of the A-AP.

M-AP can make a state change command, for instance when it needs A-AP to move from *idle-1* to *idle-2* mode or from *idle-1* to *connected mode*. To perform the state change, the M-AP sends control information to the A-AP, including DRX parameters, update interval and state change command. If the control signaling does not indicate state change, the A-AP continues sending the ESI according to the previous DRX parameters.

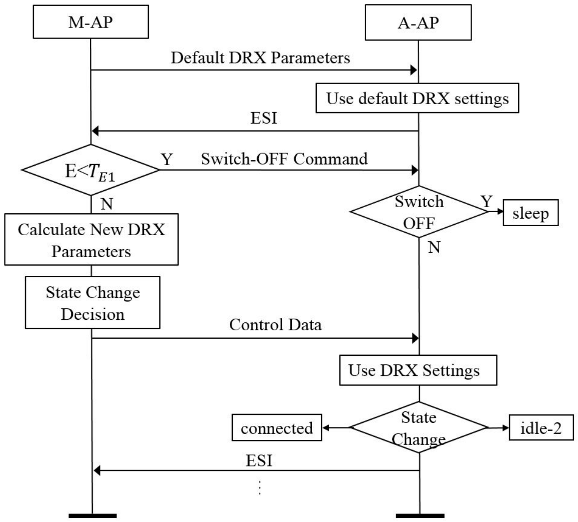


Fig. 4. Signaling between M-AP and the A-AP during *idle-1* mode.

C. idle-2

During *idle-2 mode*, AC-TRx is active, and depending whether (downlink) DL- or (uplink) UL-based mobility is employed, A-AP transmits/receives reference signals (RSs) to/from the UEs on pre-defined time and radio resources. Fig. 5(a) illustrates DL-based mobility scheme, that UE measures the RSs, and reports its measurements to M-AP. However, in the UL-based mobility, as shown in Fig. 5(b), the associated A-AP measures the users reference signals, and reports measurement through backhaul link to the M-AP.

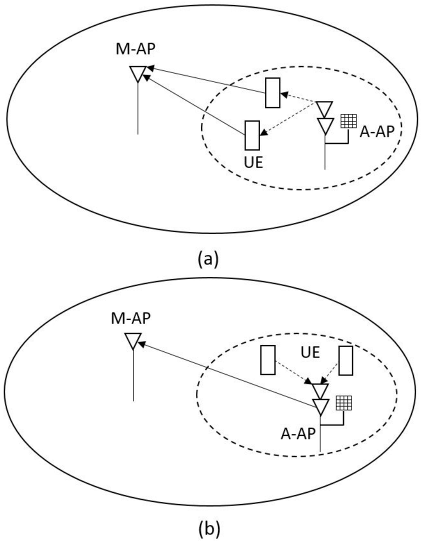


Fig. 5. Mobility procedures when A-AP resides in *idle-2* mode, (a) DL-based mobility, and (b) UL-based mobility. Dashed and solid lines refer to relevant coverage area and signaling of A-AP and M-AP, respectively.

Fig. 6 and Fig. 7 show the signaling flow of DL- and

UL-based A-AP RS measurements. In the proposed procedure, A-AP sends the ESI to M-AP for the allocation of the RS resources. The M-AP sends the allocated time and frequency resources as well as the RS sequences to A-AP and UEs using the control message. In the DL scenario, the control message contains Control Data DL 1 and Control Data DL 2 for A-AP and UE, respectively (shown in Fig. 6). Similarly, in the UL, the control message is comprised of Control Data UL 1 and Control Data UL 2 for A-AP and UE, respectively (shown in Fig. 7).

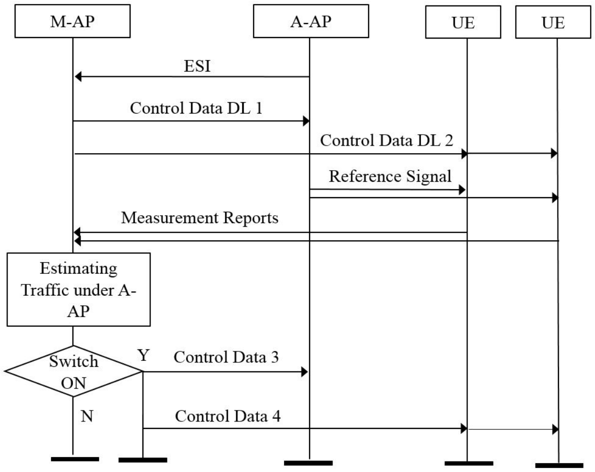


Fig. 6. DL-based mobility while UE resides in *idle-1* mode.

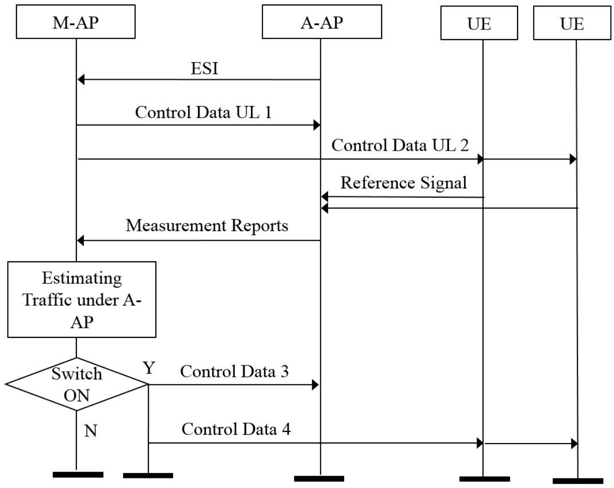


Fig. 7. UL-based mobility while UE resides in *idle-1* mode.

The M-AP allocates different resources for the RSs dynamically. The starting point and ending point of the measurements as well as the frequency of measurement report are controlled by M-AP by using above-mentioned control signaling. The A-AP can utilize this information for power saving purposes by being in the low power state mode during the time period between the RS transmissions/receptions. The power state mode can be DRX sleep mode or lower bandwidth reception in which case the Control Data DL 1 and Control Data DL 2 contain DRX/bandwidth parameterization. If M-AP, based on estimated traffic load, decides to switch on the A-AP, it would send Control Data 3 to A-AP for supporting switch-on procedures, and Control Data 4 to UEs for supporting handover procedures.

D. Connected Mode

In the *connected mode* both the access and backhaul links are active. The backhaul link radio resource management is controlled by the M-AP in order to reduce energy consumption while maintaining low latency. Occasionally, harvested energy surplus of A-AP (*full connected mode*) may occur, which it implies that the A-AP harvests and reserves more energy within the configured time period than it consumes on average. This can be quantified by an energy utilization ratio defined as the ratio of energy consumption $E_C(t)$ to available energy, comprised of residual energy of a battery $E_R(t)$, and harvested energy $E_R(t)$ during time period of t. The energy utilization ratio $E_U(t)$ over a time period t is expressed as follows,

$$E_U(t) = \frac{E_C(t)}{E_R(t) + E_H(t)}. \tag{1}$$

In another more strict definition, $E_R(t)$ can be omitted, and the energy utilization can be simply defined as the ratio of $E_C(t)$ to $E_H(t)$.

IV. TRAFFIC LOAD CONTROL

In the *energy-preserving connected mode*, the M-AP determines the traffic load to be assigned to the A-AP, so that the energy utilization ratio is always below a certain utilization threshold value. This enables continuous operation of the A-AP at the cost of capacity reduction for the A-AP. The energy utilization threshold is typically configured so that the energy reserves increase as a function of time or stay unchanged. It regulates the energy increase rate at an A-AP as determined and communicated to the A-AP by the M-AP. Occasionally, the energy utilization threshold can be set to control the discharging rate of battery.

In addition, the energy utilization ratio can be further applied to optimize the A-AP operation based on prediction of the average charging rate of the battery within a certain period. For a time period ahead, the M-AP may determine the average amount of energy that the BH-TRx and AC-TRx would require based on the assigned traffic load. At the same time the A-AP can predict the amount of harvested energy.

Maintaining the energy utilization ratio above the utilization threshold implies that more energy is generated than consumed. Furthermore, the expected energy utilization ratio $\bar{E}_U(t)$ is expressed as ratio of the expected values over a time period t as follows,

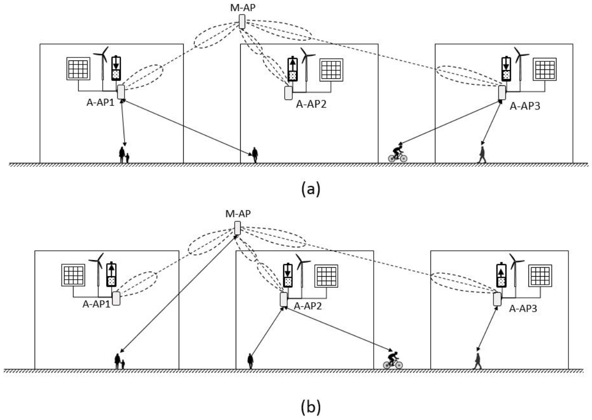
$$\bar{E}_U(t) = \frac{\bar{E}_C(t)}{\bar{E}_R(t) + \bar{E}_H(t)}, \quad (2)$$

where bar notation refers to predicted values of the corresponding quantities.

If the actual energy utilization is higher than the predicted value, either traffic load increase or reduction in generated energy are occurred. As a result, M-AP would require to reduce traffic load for next time period.

M-AP may distribute the traffic load among its associated A-APs, taking into account the battery level and the energy utilization ratio of each. Therefore, depending on the traffic load, M-AP may allow some of A-APs, typically the fully charged ones, to operate in the *full connected mode* with the energy utilization ratio above the utilization threshold. This could effectively reduce the traffic load of neighboring A-APs with lower battery levels, providing them adequate time to charge their batteries by operating at energy utilization ratio below the utilization threshold.

The optimization of the energy and traffic requirements can be performed by the M-AP by user assignments to APs, DRX/DTX, and bandwidth adaptation of the A-APs. Fig. 8 illustrates an example of user assignment among A-APs as controlled by M-AP. In Fig. 8(a), the A-AP2 is offloaded to increase energy utilization and allow some time to charge battery. When the battery in A-AP2 is charged, the A-AP2 is transferred to *connected mode*, and a partial transfer of user load to A-AP2 from the other A-APs may occur as determined by the M-AP. In this example, and as shown in Fig. 8(b), the M-AP may decide to fully offload A-AP1 (preferably changing its mode to idle-mode), and partially offload to A-AP3, so as the latter operates with an energy utilization ratio that is greater than the utilization threshold.



(a)

(b)

Fig. 8. User association among A-APs as controlled by M-AP: (a) A-AP2 is offloaded to increase energy utilization and charge battery (b) partial transfer of user load to A-AP2 to allow for full and partial offload of A-AP1 and A-AP3, respectively.

V. POWER USAGE CONTROL

Two different power usage control candidates can be considered for energy harvesting UDNs, 1) A-AP centric and 2) M-AP centric as shown in Fig. 9 and Fig. 10, respectively. In the A-AP centric approach, the A-AP reports its ESI (energy utilization, battery charging level, power consumption) to the M-AP; and then M-AP predicts the future traffic load based on the previous time periods. The M-AP re-configures the new utilization threshold, and signals to the A-AP. A-AP by using the thresholds received from the M-AP adjusts the power consumption control parameters such as total transmit power, discontinuous transmission parameters and bandwidth to keep the energy utilization within the threshold. In the M-AP centric method, M-AP governs the A-APs by sending the control parameters to the target A-AP.

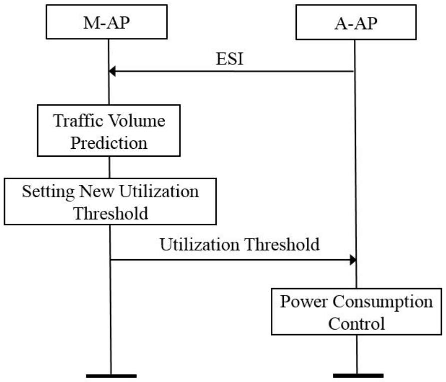


Fig. 9. A-AP based power consumption control.

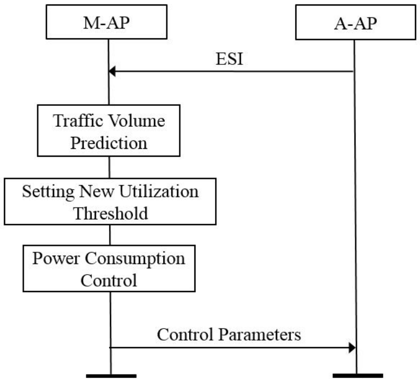


Fig. 10. M-AP based power consumption control.

Fig. 11 illustrates the A-AP power consumption profiles for each of the modes. During *sleep mode* both BH-TRx and AC-TRx are inactive, and power consumption is minimum. During the *idle-1* mode the power consumption is reduced by utilizing DRX scheme for backhaul; the DRX cycle can be enlarged since typically there is no low latency requirement at this stage. During the *idle-2* mode, in addition to the backhaul DRX, A-AP periodically transmit or receives RSs to or from UEs. Finally, during *connected mode*, both BH-TRx and AC-TRx are active, and it is assumed that the backhaul power consumption is constant, while DTX/DRX are activated for AC-TRx.

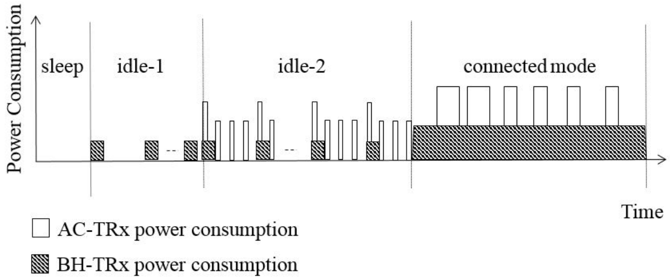


Fig. 11. Illustration of power consumption of A-AP during *sleep*, *idle-1*, *idle-2* and *connected modes*.

VI. CONCLUSION

In this work, we investigated the essential signaling for A-APs aiming to provide adequate network signaling to reduce and manage power consumption of A-APs. The measurement reports and switch off/on, energy utilization, control information and ESI are proposed in order to enhance the sustainbility of network by adjusting its topology to the traffic demand by switching off some A-APs or controlling user associations. In the future work, we will investigate and analysis the overall power consumption and capacity of the proposed network architecture and signaling, using system level simulations.

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