Future Evolution in Wireless Network Architectures: Towards a 'Cloud of Antennas'

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***Abstract*—This paper highlights the significant evolutionary potential in wireless communication networks, taking account of falling costs of RF hardware and increasing availability of powerful centralized signal processing. This so-called 'cloud of antennas' allows a central radio controller to manage a large number of remote antennas (RAs) with increasing control over their radio and radio access network behavior. By introducing autonomous terminal reporting and coordination of broadcast signaling over many RAs, the concepts of a self-organizing, and terminal-centric network are described. These could lead to significantly improved flexibility in the network deployment, reduced downlink transmit power, and reduced control signaling load for the ordinary management of the terminals. The CoA is also compared with other approaches currently being researched.**

I. Introduction

The mobile broadband market is growing rapidly, bringing with it rising customer expectations, a proliferation of smartphones, and increasing data and signaling traffic loads for mobile network operators (MNOs) [1]. Simply building ever-denser networks using current basestation designs is not a viable business option for an MNO since the high and difficult-to-reduce costs associated with equipment, site rental and operations and maintenance (O&M) can make it expensive and high-risk. An MNO could instead turn to technological advances made in radio access networks (RANs) in recent years, and deploy multiple-input multiple-output (MIMO), inter-cell interference control (ICIC), coordinated multi-point (CoMP) transmission and other such features [2]. But these can only improve capacity and performance to a certain extent: once the available spectral efficiency gains from new techniques have been fully exploited, the next call is for greater bandwidth. New spectrum licenses are expensive and rare, however [3]. Therefore, an approach to network design is needed that relaxes the constraints of current approaches.

This paper discusses how network architecture changes which exploit a future where research and development will lower the cost of network radio equipment and reduce its power consumption so that MNOs can afford to deploy antennas at much greater densities than today. With many more remote antennas (RAs) in the network, significant gains could be available from careful coordination among them. Furthermore, it becomes attractive to centralize the increased processing load into cloud computing facilities and provide high-speed backhaul from simplified RAs to central radio controllers (CRCs). This gives the CRCs the possibility of flexibly controlling many RAs and taking much control of the radio access network (RAN) to the center, with correspondingly coordinated behavior at the RAs. A network with such an organization is here termed a 'cloud of antennas' (CoA).

In what follows, Section II outlines the relevant challenges facing MNOs today, and possible responses to them. This indicates that a CoA approach is a good solution, and the basic architecture is considered in Section III. Section IV considers in detail some physical-layer re-organizations the CoA offers, and Section V differentiates its features from other current research directions. The paper is summarized in Section VI.

II. Challenges and Opportunities

This section briefly discusses some of the principal relevant challenges facing current cellular MNOs and possible overarching approaches to solving them.

A. Challenges

1) Rising and diversifying data traffic: It has been estimated that total mobile data traffic will rise some 80% year-on-year between 2011 and 2016, reaching a total of some 10 EB/month in four years' time [1]. With this comprising many different types of data traffic, such as mobile web data, mobile VoIP, and machine-to-machine data to name a few, wireless networks will need to grow in both capacity and versatility to efficiently handle the demands to be made of them. However, the volume of data is growing much faster than revenues [4], so the cost of supporting the increased traffic cannot be met simply by increasing charges to customers.

2) Dynamic workload vs. low utilization: The diurnal variations in traffic loading on a network are well known from studies in 'green' radio [5]. But a MNO's default position is to provision for the peak loading, thus over-provisioning for much of the day. The cost of providing sufficient network capacity can potentially outstrip the additional revenues that network expansion may produce. Moving away from peak provisioning in favor of a network that provisions intelligently is thus an interesting prospect.

3) Interference vs. network capacity: Densification of a network can cause rising interference as, e.g. microcell sites in a large busy city may already be only 100 – 250 m apart [6] and relying on dense frequency reuse. Simple densification from this point could make radio interference severe, requiring inter-cell coordination and causing potential reductions in neighboring cells' capacity and coverage. A more dynamic network architecture would aid operation in such scenarios.

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4) Network growth vs. total cost of ownership: The discussion in, e.g., [7] breaks down the total cost of ownership of a cellular network. Some areas are not amenable to research and development, notably civil works, site rental, and O&M. These are at present thus a fixed cost load in the growth of an operator's network. An evolution of the RAN needs to *also* target these other costs so that cellular network expansion becomes a lower-cost and therefore lower-risk proposition. Making it possible to lower the complexity, size and power consumption of huge numbers of RAs in favor of the economies of scale offered by CRCs can help achieve this.

B. Responses

1) High-density RANs: RANs have been naturally increasing in density (in terms of the number of basestations) over time as the most direct means to increase network capacity. In the future, one vision is of a ubiquitously-available RAN with each mobile device typically in sight of many more cell sites than at present. New radio equipment will therefore need to be physically small, light and power-efficient; capable of supporting the advanced technologies in current networks and possessed of enough flexibility to support future changes; and low-cost and easy to manufacture. Such development eases the deployment cost for MNOs and can lead naturally to the kind of physical hardware scenario envisaged in this paper.

2) Centralized network processing: With many in-field sites to support, coupled with a need to minimize rental costs and electricity consumption, significant processing loads can be moved to centralized computing facilities, which may be cloud-based. The prospect is of a split in processing capability between the edge of the network and a CRC. This could dramatically increase the computational capabilities of a network whilst benefiting from the economies of scale, and reduction of in-field site rental and maintenance, that centralization produces.

3) Ubiquitous high-speed backhaul: As processing is centralized an infrastructure is needed to transport bi-directional data between RAs and CRCs. MNOs are thus deploy optical fiber widely (or activate dark fiber they already possess). Depending on the degree of evolution, an increasing amount of data will need to flow bi-directionally between RAs and CRCs. Note that a RA-CRC link could be direct or indirect, but in either case an assumption of this paper is that the backhaul is a much less significant restriction than is the air interface.

III. A Cloud of Antennas

With the pressures and pathways discussed in Section II, an evolution of current cellular networks towards a more flexible, more powerful architecture is considered in this section.

A. Evolution and choices

Shown in Fig. 1 are four key steps in realizing such an architecture. Part Ⓐ shows an antenna array and baseband processing integrated into a single box, leading typically to lower transmit power losses and an antenna array connected to a baseband processing unit (BBU). Part Ⓑ is a step forward,

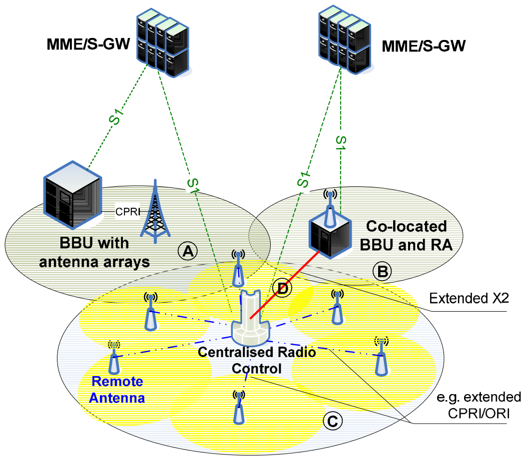

Fig. 1. RAN evolution options and pathway towards a cloud of antennas.

with the baseband processing centralized for the antenna array, but the BBU having minimal radio functions. The Common Public Radio Interface (CPRI) can be used to provide the link. Several antenna arrays may be connected to one centralized BBU, depending on the backhaul capability. Parts Ⓐ and Ⓑ are available from various vendors already.

These are both developed in part Ⓒ where there is now a powerful, centralized processing unit which provides baseband processing and as much radio control as the operator/vendor wishes to provide it with. The potentially many antennas under its control can thus have as little localized functionality as is desired. The CRC is connected to the RAs it controls via a high-speed backhaul over which it is anticipated will operate an extended CPRI-like or Open Radio Interface (ORI)-like interface. At this point, the CoA has been structurally largely realized.

A further step operators can take is to retrospectively connect their integrated BBU+RA sites to the CRC and centralize some of the control previously held at the local site (Ⓓ). This need not require hardware changes, but could need firmware changes to manage the centralization of some control.

In the consideration in this paper, the effects of the CoA architecture are at the RAN level - up to and including the inter-basestation interface (the X2 interface between eNodeBs in LTE terminology). Thus it can leave the core network unaffected, making rollout and evolution of the CoA architecture a more attractive option than if significant core network changes were required in addition to the RAN upgrades.

The RAN is connected to the core network via the well-established S1 interface. The consideration in the remainder of this paper considers evolution of the RAN-side part of the network, but upgrades to the core network following the CoA principles may also be possible in future work.

B. Components

Two key parts of a CoA-based network are clearly the CRC and the RAs. We briefly discuss the characteristics of these in a cloud-connected network architecture.

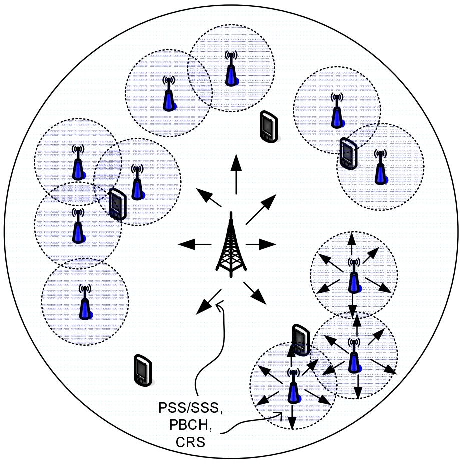

Fig. 2. Macrocell overlay on densely-deployed RAs, with some broadcast indicated. Backhaul between pico and macro RAs and CRCs not shown.

1) CRC: A CRC can take various forms. In the fully-centralized case envisaged in part 'C' of Fig. 1, it can be either a physically-localized presence or could be physically-distributed interconnected sites transparent to the RAN. Alternatively, it can be a cloud-connected legacy basestation which receives control from a centralized point, transparently to the UE. The degree to which the RAN functions are centralized is a question of operator and/or vendor choice depending on the level of evolution desired in the network.

2) Remote Antenna: An RA can take any form suitable for network deployment. It could be multi-band, wide-band or narrow-band, and can be logically connected to any number of CRCs (which will have to agree over scheduling the RA). It need not be nearby to the terminal, e.g. it could be a satellite link if so desired. In terms of evolution and deployment, it is important to note that the distribution of radio control functions between a RA and the CRC(s) it is connected to are a matter of choice: as the network evolves, the RA is likely to contain progressively reducing advanced capability and move increasingly towards being 'just an antenna'.

3) Macrocell overlay: A likely scenario both during evolution toward a CoA and even after its deployment is that there is a wide-area macrocell overlaid upon the densely-deployed RAs, depicted schematically in Fig. 2. This allows coverage to be provided in case of a temporary failure in a geographic area, as well as support for legacy terminals which are unfamiliar with the enhanced operating modes of some of the advanced RAs. It also provides useful capability in conjunction with the CRC, as discussed in later sections. A similar heterogeneous network arrangement is considered in [8].

IV. New Opportunities in a Cloud of Antennas

With many RAs under the control of CRCs, there are opportunities to configure a cellular network in ways that are not presently possible. This can take advantage of inter-cell coordination and processing gains as well as the new ability for the CRC to dynamically control many aspects of the transmissions of each RA.

In this respect, a particularly interesting scenario is where a set of RAs are all transmitting the same identifying signals to terminals (the same physical cell identity in LTE). This makes them all appear to be the same cell, and they can therefore share the work of constructing and operating cells.

In the following sections we discuss some new approaches to network construction, signaling, and terminal operation that have been developed as part of the CoA. To make the discussion concrete the specific scenario is an LTE-A network [9], and the terminology corresponds to this. However, there is no restriction in using the principles described here in other types of network, such as future versions of WiFi and WiMAX.

A. Self-constructing networks

In existing Releases of LTE, and all cellular systems, the cells transmit a set of signals, usually in broadcast, which are essential to the operation of the cell. In LTE these are:

- Primary and secondary synchronization sequences (PSS and SSS)
- The physical broadcast channel (PBCH)
- Cell-specific reference signals (CRS)

Together, these signals allow a terminal to detect the presence of a cell, synchronize to its transmissions, and obtain key basic information about how the cell has been configured by the MNO. In current systems, these would typically be broadcast from every RA since each RA forms its own cell. This is depicted by the arrowheads in Fig. 2, which would actually emanate from every RA. But when there are many RAs and they are all identified as being the same cell, considerable optimization and re-use of the broadcast signals becomes possible. In the natural, and default arrangement, considerable interference could arise on the broadcast signals, especially if the RAs are deployed densely in the CoA. The CRC also offers the opportunity to design means of controlling this.

There are many other aspects of the operation of a cell that are signaled to a terminal, either in other broadcast signals or by radio resource control (RRC) signaling directly to a terminal. Notable among them are the configurations of uplink and downlink reference signals which in LTE (and particularly future releases of LTE) may have components which are specific to a whole cell and components specific to each terminal. An evolved network operating with a CRC can obtain further flexibility and reduction in signaling loads by designing new ways of controlling these.

1) Network structure via synchronization signals: In LTE-A systems as currently specified, PSS/SSS are transmitted at fixed intervals (i.e. particular subframes) within a radio frame from a RA. However, which RA is used is allowed to change from one transmission interval to the next. Therefore, in a CoA with the CRC and/or overlaid macrocell having comprehensive knowledge of and control over the RAs, the synchronization signals can be used to signal implicitly the operation of the network. This can be done by associating the transmission of PSS/SSS in a particular subframe from a particular RA to a predefined state of the network's configuration.

(a) Reference signal configurations

The configuration in time, frequency and space of downlink reference signals (RS), such as those for estimating channel state information (CSI-RS), is in part cell-specific and therefore amenable to implicit signaling. The number of distinct CSI-RS transmitted is linked to the degree of spatial multiplexing in use, and other RS have linkages to related parameters. RS transmission is thus tightly linked to the logical, and in some cases physical, structure of the network in terms of antenna ports as presented to terminals.

By signaling the configuration of RS implicitly, the network can thus appear to a terminal to change its structure and configuration as the terminal moves and the PSS/SSS set it receives changes. The apparent spatial, temporal and spectral density and arrangement of RS to be measured by a terminal can be tailored opportunistically to each terminal's needs and their physical transmission can be an independent function of the whole network's needs at the same time.

(b) Selective broadcast

In existing systems PBCH (among other things) will usually be transmitted from every RA since each RA has its own cell and thus its own cell-specific configuration to broadcast. However, in the scenario considered here, some of the broadcast information may be the same among some — and perhaps many — of the RAs. In this case, the RA-subframe pairing can indicate, e.g. (i) that a given RA will not transmit PBCH and that terminals should obtain the relevant information from another RA or the overlaid macrocell.

Such an arrangement is a significant departure from conventional systems and could meaningfully reduce interference on the broadcast channel within the geographic coverage of a set of centrally coordinated RAs. It could also be used to reduce 'intercell' interference at the boundary between two coordinated groups. Depending on configuration, it also represents an obvious reduction in network power consumption.

2) Terminal-centric networks: In the scenario under consideration, the set of RAs from which a terminal can receive broadcast signals (of any kind) will change as the terminal moves. It is highly undesirable to perform a process akin to handover each time a terminal enters/leaves the coverage of a RA — particularly when the network is as densely deployed as envisaged in this paper. A solution to this is to give a terminal the ability to indicate autonomously which RAs it can receive signals from. Discussed in the following sections are the numerous possibilities such an innovation opens up.

(a) Presence Indication

A simple way to implement terminal presence indication (PI) is to define a particular uplink signal the terminal may transmit to indicate that it is able to receive signals from a particular RA. A readily-available choice in LTE is the random access (RA) preamble a terminal transmits when it needs access to the network, but has no uplink resources (among other purposes).

By reserving a subset of the possible preamble signatures for PI, when the network receives one it knows that a terminal has moved into the coverage area of the relevant RA. To distinguish among the RAs, the terminal can transmit a RA preamble in a timeslot (subframe) specified either by the cell ID that the RA transmits, if they transmit different identities, or by the subframe in which the PSS/SSS is transmitted if the RAs transmit the same identity, following the concept described above. Other uplink signals, such as some reserved uplink RS configurations, could also be used.

This arrangement creates a network which is responsive to the terminals' changing distribution rather than being configured by O&M. The following sections discuss some of the potential soft configuration options this creates.

(b) Autonomous reporting of network structure

The terminal can be allowed the ability to decide autonomously whether to transmit a PI with respect to a particular RA, even though it can certainly receive its signals. For example, a terminal might not transmit PI with respect to a weak RA when it can receive stronger signals from another RA — this would avoid unnecessary uplink transmissions and interference. On the other hand, a terminal which judges it is in need of high data rates or increased spatial diversity could transmit PI with respect to many or all RAs, even those with weaker received levels. The network's structure can now be responsive to a user's needs as they change over time.

(c) Geographic broadcast restriction

Signals transmitted in broadcast are, as discussed previously, currently transmitted from essentially all RAs since each forms a separate cell. However, a network with densely deployed RAs — whether they all transmit the same cell identity or different identities — which knows geographically how its terminals are distributed and when this distribution changes, need not transmit such comprehensive broadcast signals.

In general, consider that the network does not enable all broadcast signals from RAs by default, transmitting instead only the PSS/SSS that allow the terminal to detect and identify the RA. The network is thus in an enormously effective interference reduction and energy saving mode. As RAs receive presence indications from terminals, the network can enable any suitable subset of the broadcast signals to be transmitted from these RAs. For example, basic signals such as PBCH and CRS can be turned on when a terminal moves into range. As terminals vacate the coverage of a RA the signals can be switched off once again if desired.

(e) Behavioral control

Allowing terminals to engage freely in presence indication could be undesirable, especially if a terminal enters an area where RAs are already transmitting a full set of broadcast signals. Control of the PI signaling can be by permitting PI with respect to a RA only if at least some of the broadcast signals considered above are currently not being transmitted by that RA. This would suppress PIs which would not affect basic network construction, but could deprive the network of some information regarding potential aggregations of RAs suitable for a given terminal. Alternatively, a terminal could be allowed to transmit PI only when the set of RAs it can detect (via PSS/SSS) changes. This would still allow the terminal to update the network as its view of RAs changes, but would suppress some amount of potentially unnecessary PIs.

B. Smarter Signaling

With the proliferation of cells that the CoA anticipates, there is the possibility of significantly increased signaling load if smarter use is not made of existing signaling. For example, the need to communicate to/from terminals regarding resource assignment, network structure and terminal feedback could be become prohibitive, especially when combined with the terminal needing to make more measurements of received signals from many possible combinations of RAs.

Therefore, in a CoA, existing signaling will be re-used as far as possible, but enhanced to carry new information with a low additional overhead. Using the random access procedure for presence indication is a good example of this, as is using PSS/SSS to indicate network structure and operation.

V. Differentiators and New Pathways

The CoA concept shares some rationales with other fields of technical effort, with which it is here compared and contrasted.

A. Greener radio

Work on greener radio considers in part the reduction of cell size and signaling when traffic load is light, e.g. during the night. Presence indication could have the same effect, but operate from an opposite perspective, by allowing the terminal to make the decision as to whether to report an implied need for resources. It is up to the network to determine its response to a PI, but the terminal-centric CoA creates a new pathway for providing information autonomously to the network.

B. Smaller cells

Cell sizes are already tending to shrink, partly as a means to reduce the cost of rollout for operators and partly to improve coverage and capacity. In a CoA scenario where there are many RAs, there is clearly the likelihood that cells will shrink in accordance with their growing number. However, a more dramatic outcome is envisaged by a CoA architecture: a network where cells are amorphous and re-configurable and where as a result particularly cell identity and handover become much more flexible and fluid concepts. For example, the notion of handover in the case of the network signaling alterations to its structure by updating its PSS/SSS transmissions, or re-aggregating antennas in response to a changing set of RAs receiving PIs from a terminal has similarities to handover, but without any need to break or make connections.

In effect, what today would be termed a 'cell' has become extremely large and yet composed of an increased number of small coverage zones from RAs. This obtains the benefits of a 'smaller cells' deployment in terms of quality of coverage and cost of dense rollout, but avoids the problems it could bring of increased handover and higher-layer complexity.

C. Centralized processing

There are ongoing efforts to centralize the signal processing of the RAN, e.g. within NGMN [10]. The centralized RAN (C-RAN) is a key assumption of the CoA, but CoA goes further depending on how far evolved an operator's network is. We have described a network which can respond in new ways to the terminals within it, and is able to move capacity and capability around as needed. The concept of a terminal-centric, self-constructing network is a novel use for a C-RAN backend, rather than an effort to design the backend functionality alone.

VI. Conclusions and Summary

The prospect of cellular network evolution toward the concept of a CoA has been discussed with reference to the steps involved, what components are needed to enable it, and the increased capability and flexibility it could offer. A densely deployed RAN consisting of low-cost antenna units coupled to a powerful set of CRCs via a high-speed backhaul opens up numerous novel opportunities to the designer.

The concepts of a self-constructing network and a terminal-centric network have been explored. These innovations make smarter use of existing signaling so that the network and terminals can conduct the additional communications necessary to establish and administer a CoA while limiting additional overhead. These ideas are well aligned with other trends in the research arena, but the differences between CoA and other areas have been considered and represent new benefits which are not available only by relying on current work.

Thus, the benefits from emerging technologies such as green wireless, self-optimizing networks, etc., will be amplified. The simplification of network edge hardware resulting from gradual centralization of the RAN will provide coordination gains, and reduce costs by minimizing site footprint, rental costs, and electrical power consumption of in-field equipment. Moving to a CoA-based network can be gradual and still realize benefits at each stage, so an MNO adopting a CoA deployment plan will be able to profitably meet the challenges of changing technology.

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