communications to directly exchange data between them, implementing localized data replication or storage policies. In those cases, the data routing is not necessarily regulated centrally, but can be efficiently distributed, using appropriate cooperation schemes. In the architecture, therefore, the control of data management schemes can be performed centrally at the Orchestrator, locally at the LMs, or even at individual devices, as appropriate. Data management operations become distributed, and exploit devices which lie between source and destination devices, like the use of proxies for data storage and access [24], discussed in more detail in Section VI.

C. Multi-tier organization

In the proposed architecture, cells are organized in different tiers depending on the communication requirements of the industrial application they support. LMs of cells in different tiers consider the use of different management algorithms to efficiently meet the stringent requirements of the different industrial applications they support. For example, regarding scheduling, a semi-persistent scheduling algorithm could be applied in LTE cells to guarantee ultra-low latency communications; semi-persistent scheduling algorithms avoid delays associated to the exchange of signaling messages to request (from the device to the eNB) and grant (from the eNB to the device) access to the radio resources. However, semi-persistent scheduling algorithms might not be adequate for less demanding latency requirements due to the potential underutilization of radio resources. The different requirements in terms of latency and reliability of the application supported by a cell also affects the exact locations where data should be stored and replicated. For example, in time-critical applications, the lower the data access latency bound is, the closer to the destination the data should be replicated.

The requirements of the nodes connected to a cell also influence the type of interactions between the LM of the cell and the Orchestrator. LMs of cells that support communication links with loose latency requirements can delegate some of their management functions to the Orchestrator. For these cells, a closer coordination between different cells could be achieved. Management decisions performed by LMs based on local information are preferred for applications with ultra-high demanding latency requirements (see Fig. 3).

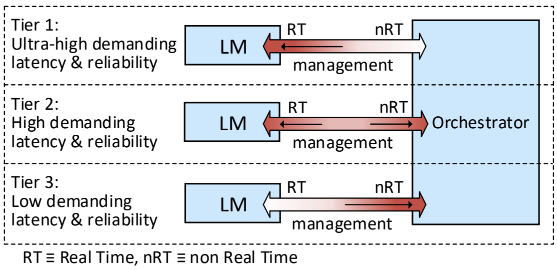

Fig. 3. LM-Orchestrator interaction at different tiers of the management architecture.

V. VIRTUALIZATION AND SOFTWARIZATION

Efficiency, agility, and speed are fundamental characteristics that future communication and networking architectures must accomplish to support the high diverging and stringent performance requirements of future communication systems (including but not limited to the industrial ones) [25]. In this context, the communication and data management architecture proposed in this paper considers the use of RAN Slicing and Cloud RAN as enabling technologies to achieve the sought flexibility and efficiency.

A. RAN Slicing

The proposed architecture considers the use of heterogeneous communication technologies. The assignment of communication technologies to industrial applications does not need to necessarily be a one-to-one matching. There is a clear trend nowadays in designing wireless technologies such that they can support more than one type of application even belonging to different "verticals", each of them with possibly radically different communication requirements. For example, LTE or 5G can be used to satisfy the ultra low-latency and high reliability communications of a time-critical automation process. The same networks could also support applications that require high throughput levels, e.g. virtual reality or 4K/8K ultra high definition video. This is typically achieved through network virtualization and slicing to guarantee isolation of (virtual) resources and independence.

In the proposed architecture, each cell can support several industrial applications with different communication requirements. The industrial applications supported by the same cell might require different management functions or techniques to satisfy their different requirements in terms of transmission rates, delay, or reliability. Moreover, it is important to ensure that the application-specific requirements are satisfied independently of the congestion and performance experienced by the other application supported by the same cell, i.e., performance isolation needs to be guaranteed between different applications. For example, the amount of traffic generated by a given application should not negatively influence the performance of the other application. In this context, we propose the use of RAN Slicing to solve the above-mentioned issues. RAN Slicing is based on SDN (Software Defined Networking) and NFV (Network Function Virtualization) technologies and proposes to split the resources and management functions of a RAN in different slices to create multiple logical (virtual) networks on top of a common network [26]. Each of these slices, in this case, virtual RANs, must contain the required resources needed to meet the communication requirements of the application or service that such slice supports. One of the main objectives of RAN Slicing is to assure isolation in terms of performance [26]. In addition, isolation in terms of management must also be ensured, allowing the independent management of each slice as a separated network. As a result, RAN Slicing becomes a key technology to deploy a flexible communication and networking architectures capable to meet the stringent and diverging communication requirements of industrial applications, and in particular, those of URLLC.

Each slice of a physical cell is referred to as virtual cell in this work (Fig. 4). Virtual cells resulting from the split of the same physical cell can be located at different levels of the multi-tier architecture depending on the communication requirements of the applications. Each virtual cell implements the appropriate functions based on the requirements of the

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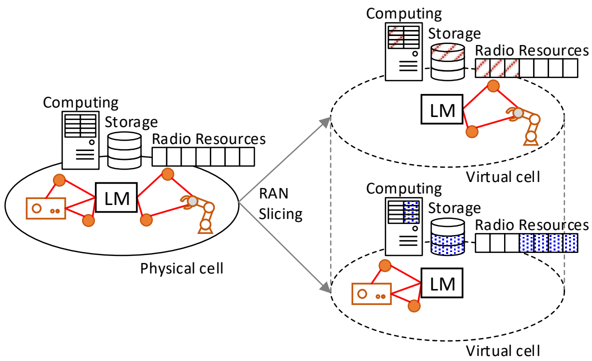

Fig.4. Virtual cells based on RAN Slicing.

application supported and must be assigned the RAN resources required to satisfy the requirements of the communication links it supports. The amount of RAN resources (e.g., data storage, computing, radio resources, etc.) allocated to each virtual cell must be dynamically adapted based on the operating conditions such as the amount of traffic, or the link quality. The Orchestrator is the management entity in charge of creating and managing RAN slices or virtual cells. Thanks to the reports received from the LMs, the Orchestrator has a global view of the performance experienced at the different (virtual) cells. As a result, it is able to decide the amount of RAN resources that must be assigned to each virtual cell to guarantee the communication requirements of the applications. With respect to data management functions, they will operate on top of the virtual networks generated by RAN Slicing. However, the requirements posed by data management will determine part of the network traffic patterns. Therefore, RAN Slicing defined by the Orchestrator might consider the traffic patterns resulting from data management operations to optimize slicing itself.

B. Cloudification of the RAN

Cloud-based RAN (or simply Cloud RAN) is a novel paradigm for RAN architectures that applies NFV and cloud technologies for deploying RAN functions [27]. Cloud RAN splits the base station into a radio unit, known as Radio Remote Head (RRH), and a signal processing unit referred to as Base Band Unit (BBU). The key concept of Cloud RAN is that the signal processing units, i.e., the BBUs, can be moved to the cloud. Cloud RAN shifts from the traditional distributed architecture to a centralized one, where some or all of the base station processing and management functions are placed in a central virtualized BBU pool (a virtualized cluster which can consist of general purpose processors to perform baseband processing and that is shared by all cells) [27]. Virtual BBUs and RRHs are connected by a fronthaul network. Centralizing processing and management functions in the same location improves interworking and coordination among cells; virtual BBUs are located in the same place, and exchange of data among them can be carried out easier and with shorter delay.

We foresee cloud RAN as the baseline technology for the proposed architecture, to implement hierarchical and multi-tier communication management. Cloud RAN will be a key technology to achieve a tight coordination between cells in the proposed architecture and to control inter-cell and inter-system interferences. Cloud RAN can support different functional splits that are perfectly aligned with the foreseen needs of industrial applications [28]; some processing functions can be executed remotely while functions with strong real-time requirements can remain at the cell site. In the proposed communication and data management architecture, the decision about how to perform this functional split must be taken by the Orchestrator considering the communication requirements of the applications supported by each cell.

The Cloud RAN architectural paradigm allows for hardware resource pooling, which also reduces operational cost, by reducing power and energy consumption compared to traditional architectures [27], which results an attractive incentive for industrial deployment. The cloudification of the RAN will also leverage RAN Slicing on a single network infrastructure, and will increase flexibility for the construction of on-demand slices to support individual service types or application within a cell.

VI. Decentralized Data Management

The suggested architecture can be used in order to efficiently deploy data management functions over typical industrial IoT networks. Initial results show that the decentralized data management scheme of the proposed architecture can indeed enhance various target metrics. For example, as shown in [24], by using a subset of the data management functions coming from our architectural design, the industrial network operator is able to significantly improve the data access delay. More specifically, in large scale networks of sensing and actuating nodes, given a set of data, the sets of nodes generating and requesting them, and a maximum data access delay L_{max} that requesting nodes can tolerate, the LM (or the Orchestrator) can efficiently identify a limited set of proxies in the network where data should be stored. Given the mentioned constraints, the computationally difficult problem of finding which network nodes to select as proxies can be solved at the LM using appropriate heuristics. Then, the proper assignment of requesting nodes to corresponding proxies can guarantee that the average access delay in the network stays below the given threshold. In fact, this kind of method can significantly outperform both entirely centralized and distributed approaches (which do not typically take into account maximum access delay thresholds), both in terms of access latency and in terms of maximum delay guarantees. For example, in Fig. 5 a simulative performance comparison is displayed. We compare (i) a decentralized data

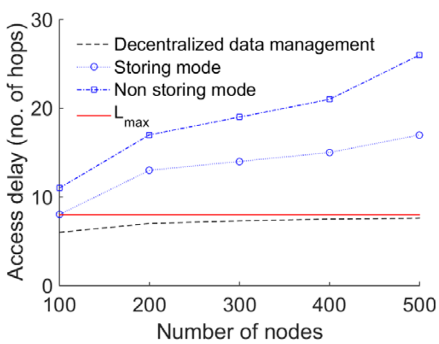

Fig. 5. End-to-end latency (number of hops) for three alternative solutions (simulation under ideal conditions [24]).

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management approach which adopts the suggested architecture, (ii) a centralized approach where a single node (the LM being the natural candidate for this) stores all the data and serves all data requests coming from all nodes (referred to as non-storing mode), and (iii) a distributed approach which routes the data through some intermediate nodes (between providers and requestors) defined as the lowest common ancestors of the routing tree, assuming nodes are topologically organized according to a tree structure (referred to as storing mode). Results show that our decentralized method, where the LM decides which nodes should act as proxies for data storage, is able to guarantee the delay requirements of the applications, and significantly outperforms both a totally centralized approach, and also a distributed approach where data replication does not take into account the specific data generation and request patterns of the application.

VII. CONCLUSIONS

A software defined heterogeneous, hierarchical and multi-tier communication management architecture with edge-powered smart data distribution strategies has been proposed in this paper to support ubiquitous, flexible and reliable connectivity and efficient data management in highly dynamic Industry 4.0 scenarios where multiple digital services and applications are bound to coexist. The proposed architecture exploits the different abilities of heterogeneous communication technologies to meet the broad range of communication requirements demanded by Industry 4.0 applications. Integration of the different technologies in an efficient and reliable network is achieved by means of a hybrid management strategy consisting of decentralized management decisions coordinated by a central orchestrator. Local management entities organized in different virtual tiers of the architecture can implement different management functions based on the requirements of the application they support. The hierarchical and multi-tier communication management architecture enables the implementation of cooperating (to optimize performance), but distinct (to achieve modularity and manageability of the architecture components) management functions to maximize flexibility and efficiency to meet the stringent and varying requirements of industrial applications. The proposed architecture considers the use of RAN Slicing and Cloud RAN as enabling technologies to meet reliably and effectively future Industry 4.0 autonomous assembly scenarios and modular plug & play manufacturing systems.

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