Meta-Intelligence for the Meta-Continuum

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Abstract—Recent advances in artificial intelligence (AI) and distributed computing technologies have enabled the decentralisation of intelligence in computing systems. Decentralised intelligence refers to localised, autonomous problem-solving and decision-making capabilities in a system without central planning or control. The meta-continuum extends the compute continuum by comprising a flexible, goal-oriented aggregation of resources that can assemble and disassemble on demand. To fully realise the potential of the meta-continuum, meta-intelligence is needed - intelligence about how to distribute, integrate and optimise intelligence across a decentralised system. Meta-intelligence preserves the autonomy of system components while enhancing their collective problem-solving power through collaborative knowledge sharing and emergence. By enabling rapid, tailored development of intelligent software agents and facilitating collaboration, meta-intelligence could radically transform software engineering and application management, enabling a shift to collaborative development and deployment for distributed, intelligent applications.

Index Terms—Meta-intelligence, Decentralised learning, Distributed architectures, Self-organisation

1 Motivation

The computing world is undergoing rapid and continuous evolution as new technologies and approaches emerge to cater to the increasing demand for sophisticated and intelligent services that can improve user experience. One such approach is the cognitive cloud [1], which enhances the capabilities of cloud-based applications and services by incorporating cognitive technologies such as machine learning and reasoning [2], [3]. If, on the one hand, according to a survey by IBM, companies that embraced cognitive computing capabilities have already noticed considerable investment returns [4]. On the other hand, Gartner predicts that "organisations will need to invest in tools and technologies that support distributed infrastructure" to keep up with the demands of modern applications [2]. Distributed applications have become increasingly important in our daily lives, with a growing number requiring flexible and dynamic use of compute and network resources [5]. Cloud technologies played a crucial role in providing the infrastructure for these dynamic applications [6]. However, the only viable approach to achieving ultra-scalability to support modern applications is decentralising the infrastructure and bringing resources near users and data [7] by placing applications and data along the compute continuum encompassing cloud and edge resources. This approach is undertaken by the cognitive continuum that attempts to bring cognitive cloud principles and approaches to the entire set of resources that span from the cloud to the network's edge. Some more advanced visions define the concept of the meta-continuum, intended as a continuum composed of adaptable, goal-oriented resources that can aggregate in arbitrary and optimised ways based on intents and needs as a compelling framing. Resources within the meta-continuum are flexible and reconfigurable rather than static components with fixed roles, scale or scope. They can assemble and disassemble as required to meet evolving objectives by relying on fully decentralised interactions. A decentralised system comprising many small, distributed components is less vulnerable to failures in any single part and can continue operating even if individual nodes go down. It can adapt more easily to changes, evolving needs, and unforeseen conditions by dynamically reconfiguring relationships between loose-coupled components. Decentralisation enhances privacy and security by preventing any single entity from accessing everything and allows for localised, tailored solutions responsive to specific needs. With decentralisation, sensitive data and critical services remain under more local control, but efficient use of resources and achieving economic benefits of scale become more difficult. There are good reasons to decentralise certain systems and services, but also case-by-case considerations of whether and how much decentralisation makes sense versus alternative architectures.

A relevant target of current developments in the decentralisation of systems relates to the decentralisation of intelligence throughout sectors and value chains, using local sensing, learning, and decision-making to coordinate across the system without relying on centralised planning or control. In a decentralised approach, intelligence emerges from the bottom up through specialised, localised bits of intelligence developed by individual industries, suppliers, and other constituents based on their unique needs, structures, and functions.

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2 Current Status

Recent years have seen tremendous progress in the field of artificial intelligence. It is pervasively infusing all the environments, both anthropic and digital ones. This also applies to computing and network infrastructures where artificial intelligence enables novel approaches to data management, analytics, and decision-making capabilities, also

at the network edge. There is a growing demand for more distributed, localised intelligence and control in edge computing, IoT systems, and cyber-physical infrastructures. We are witnessing works focused on establishing technologies and emerging system concepts based on the cloud-edge computing paradigms by building on different computing, connectivity, IoT, AI and cybersecurity elements. Several key achievements were realised or are under active development, that includes prototype edge platforms, edge AI frameworks, trustworthy edge computing architectures, edge-native AI algorithms, and edge cybersecurity solutions. There is active work on edge AI engines, edge cybersecurity frameworks, and system integration approaches that can deliver highly automated, adaptive, intelligent and trusted systems at scale. This will enable new capabilities for distributed situational awareness, automated decision-making, optimised resource allocation, predictive maintenance, and personalised healthcare that reshape businesses, infrastructure, and societies. With more edge intelligence and autonomy, the future of cloud-edge IoT converges on ubiquitous, pervasive and seamless computing to transform our world in profound and sustainable ways. This local intelligence also learns how to cooperate, adapt, and integrate, thereby self-organising the system into intelligent, collective behaviours that boost competitiveness.

The relevance of the effective development of solutions and technologies supporting the decentralisation of intelligence is demonstrated by the huge amount of work conducted in distributed and federated learning, which enables intelligent solutions to be pervasively adopted and deployed while ensuring privacy and protection over user data.

3 Research Challenges

Federated (and most decentralised) learning approaches allow collective experiences to be gathered and leveraged to improve the intelligent behaviour of every single entity participating in the collectivity. However, in most cases, the AI model's collaboration paradigm, topology, and structure are pre-defined. This limits open, dynamic and opportunistic collaboration possibilities across different entities if not foreseen in advance. Such a limitation is particularly relevant regarding the meta-continuum, which is, by definition, dynamically composed and made of a large set of heterogeneous resources provided by different owners. This calls for bringing decentralised intelligence for application and resource management in the meta-continuum to the next level, the **meta-intelligence**. Meta-intelligence is intelligence about intelligence, as such, it needs to be able to **understand, monitor, analyse and optimise intelligent systems and cognitive capabilities**. It proposes distributing intelligence at multiple scales - micro (agent), meso (cluster) and macro (global). Consequently, intelligence needs to be **hyper-distributed rather than concentrated in any one entity or authority**.

Meta-intelligence preserves autonomy and self-determination while enhancing and distributing intelligent capacity across networks. It must ensure the **independence and self-governance of agents/components without centralised control, with intelligent collaboration being voluntary and non-mdandatory**. Meta-intelligence generates **collective and distributed problem-solving power by integrating intelligent agents**. It enables capabilities greater than any individual component via **collaborative experimentation, knowledge sharing and emergence**. Meta-intelligence is **adaptive and specialised**. Different agents/components can develop intelligence attuned to local needs, conditions, objectives, and constraints. But they also adapt knowledge and problem-solving approaches based on interactions, **allowing specialisations to inform each other innovatively and reciprocally over time**. Meta-intelligence can **harness the potential of external services based on artificial intelligence themselves**, such as large trained models (e.g., ChatGPT, Claude-Instant, Dragonfly, etc.), to deeply **transform how existing ICT technologies operate and interact with the physical world**. Design, development, placement and management processes targeting hyper-distributed applications can be radically transformed as well as **how systems and software are implemented, deployed, and evolved**. Advances in AI, especially around machine learning, natural language processing, and reasoning, could enable far more **rapid development of intelligent, specialised software agents attuned to industries, regions, and other stakeholders' unique needs**. Hyper-distributed architectures would allow these AI agents to connect, coordinate, and even fuse their intelligence together while **preserving autonomy and self-determination**. **Digital twins and blockchain networks could integrate with AIs**, providing real-time visibility, optimisation, provenance and exchange of data/resources across decentralised, AI-infused systems.

Meta-intelligence-equipped meta-continuum enables the shift of software engineering and application management from a mindset of controlled, pre-defined, mostly centralised planning to a continuous, distributed, collaborative process based on experimentation and learning, happening dynamically, by chance and goal-oriented among distributed entities.

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