A Survey of Internet Protocol and Architectures in the Context of Emerging Technologies

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Abstract—**The Internet technologies need an overhaul to support next-generation of applications requiring communications between machines and humans. This paper is a survey of the state of current internetworking architecture and its engineering properties. The purpose of this paper is to highlight the aging of original design goals and motivations. We aim to formulate a new set of guidelines that maybe used to postulate design principles of the new network architectures.**

Keywords–Internet architecture, Internet Protocol, Routing, Switching; Ossification, layering.

I. INTRODUCTION

The Internet has grown remarkably since its foundational work was published as *A Protocol for Packet Network Intercommunication* [1]. This specification was developed into Transmission Control Protocol/Internet Protcol (TCP/IP) in compliance with the Internet design principles [2]. While the Internet has proven to scale and support diverse set of applications and users, the more recent technological advancements such as Machine to Machine (M2M) communications, connected or live Augmented Reality/Virtual Reality (AR/VR), Vehicle to Anything (V2X) communications etc., impose new requirements on connectivity that did not exist before. The applications based on these technologies are far more stringent about both network resource constraints and packet delivery guarantees. The current architecture lacks several artifacts to guarantee support for real-time, low latency and reliable services. In this regard, several new network architectures have been proposed with different motivations; however, none of them have been attentive to strict quality of service constraints.

In this paper, we systematically analyse effects of current architectural and engineering design choices (both adversely and favorably) that can be used to understand specific gaps in the context of emergent applications. These effects are identified as: 1) the commercial effect, 2) layering, 3) addressing, 4) Ossification, and 5) services; They will be discussed in detail to highlight their influence and stronghold on the current state of the Internet. In this study we show that the current principles of inter-networking are not sustainable to serve applications built for the use of emerging technologies. The paper further aims to achieve the following:

(a)

1) Briefly describe use cases catogarized as emerging applications.
2) Provide an analysis of original design principles and corresponding engineering effects.
3) Guidelines to be taken under consideration when designing new or evolving the current Internet architecture.

The paper is organized as follows: Section II briefly mentions future network architectures related work, while Section III starts with the background and motivation for this paper, in Section IV we analyse the original concept and design goals of Internet architecture. Section V is a discussion on the engineering effects of the Internet and their analysis in context of emerging applications. Section VI proposes properties to be taken in to account for designing new internet architecture. In Section VII, we expose the factors that will drive the need for new Internet architectures. We conclude with a summary of this survey in Section VIII.

II. RELATED WORK

This paper primarily analyses several published works of Kahn, Cerf and Clark. Their insights and reflections on the design of the Internet have been taken into consideration in the context when analysing the current state of Internet.

The discussion for new architecture has come up several times. In fact, immediately following the Internet impact, guidelines for the future network architecture were produced in RFC1287 [3]. It revealed several interesting shortcomings relating to addresses, multi-protocol architectures, traffic control and security. It also mentioned that service awareness was necessary in general and specifically for voice, video and teleconferencing type of applications.

There has been continuous effort in building next generation internet encompassing from evolutionary to clean-slate approaches [4]. More recently, some of the large-scale future internet initiatives eXpressive Internet Architecture (XIA), Future Internet Research and Experimentation (FIRE), Named Defined Networks (NDN), Software Defined Networking (SDN), etc. [5] have been proposed to solve known problems. None of these initiatives can be qualified as either failed or successful projects since they did not get deployed and tested in live environments. In principle, the network community understands a need to upgrade the Internet architecture and design, however, none of the efforts have been able to stir a serious interest from commercial sector. Several federated and national initiatives such as Future Internet Architecture (FIA) [6], 4WARD [7], AKARI [8], Study Group 13, Future Networks (SG13) [9] and many more do not transition from research to commercial mainstream even

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after having undergone thorough experimentation (FIRE [10], Global Environment for Network Innovations (GENI) [11]).

An obvious reason is the growth in Internet and its ability to absorb many motivations of new architectures. Another possible reason may be that the new solutions focus on a particular problem-domain instead of taking the holistic approach along the lines of design principles. Our contribution focuses on support for communication aspects of current and future technological advances in medicine, manufacturing, city planning and automating vehicles etc as a driver to review current Internet design.

III. Background

Clark's Internet design philosophy serves as the guiding principles of the Internet architecture [2]. According to Kahn [12], the reference architecture and TCP/IP as an implementation are often used interchangeably, but that was not the intent. The reference design of the Internet was a logical framework for interconnection of independent networks and TCP/IP is one such instance that implemented it. Kahn also admits that the reference architecture itself does not assume the idea of linking different networks together will result into a single system. The vision was to foster multiple implementations serving different systems from the same abstract architecture. With the TCP/IP, this generality of the design was lost which prevents the evolution of Internet from its current state without disruption [4]. The TCP/IP resists change and on-boarding new services to support new applications is a difficult task.

Traditionally, services with special constraints in networks concern with delivery of data through Quality Of Service (QoS) parameters that are represented by coarse grained means of allocating network resources (e.g., buffers and bandwidth) using code points [13] [14] on per hop or end-to-end [15] basis. For example, a service characteristic such as lower latency may be marked to code-point that indicate 'real-time' traffic. In contrast, the emergent services for scenarios such as M2M, V2X, AR/VR communications are associated with extremely strict resource constraints and absolute guarantees of QoS in the network. For example, industrial automation relies on M2M communication to achieve reliable interaction between different type of machines with a fine-grained granularity in delay variation. Any failure to deliver data in precise time-interval could cause machines go into stall mode halting the over all production. Similarly, in V2X scenarios, the infrastructure should be able to gather live information from multiple sources such as approaching signals, road conditions, and other vehicles to make real-time decisions about public safety and streamlining traffic flow; while ensuring the decision is fed to an autonomous vehicle instantaneously; any delay makes information stale and unusable. Rest of the paper collectively refers to these use cases as *emerging applications*.

IV. Foundations of The Internet Architecture

The primary goal of the reference internet architecture is to provide an effective technique to multiplex packet switched data over interconnected networks. There were seven additional goals (see [2]) that had to be met at the time of the internetworking design. While these design principles are generally accepted, as times change and technologies evolve, some of the original principles cannot be followed as is.

The first goal, '*Internet should continue to provide communication service...*' is about suvivability and fate-sharing. In networks, fate-sharing suggests that it is acceptable to lose the state information of an entity, if the entity itself is lost. This principle entirely takes away the responsibility of reliability in the network which will require some knowledge of relevant state.

There is an indirect consequence of this principle, that the network is stateless with no knowledge besides forwarding information of an entity. While, it is true that maintaining an overall state of all the sessions in the Internet is unmaintainable; there are specific scenarios where it provides resilience, robustness through faster recovery and security. There is also a question of what determines that an entity is lost. Whether a session was withdrawn gracefully or due to failure such as congestion or packet loss in the network can not be determined by the network itself. In industrial interent, M2M communication scenarios require bounded latency and are sensitive to delays, such connections benefit from having state in the network. Relaxing this fate-sharing principle will help determine fate of an entity. In Internet of Things (IoT) communications entities would goto sleep mode but may still have associated active state in the network for high reliability scenarios. Therefore, future internet design goal may consider fate-sharing to be optional or need-basis; Certain type of services, such as those requiring zero packet loss, in-network stateful buffering can help trigger retransmissions from a nearer hop without involving end hosts.

Additionally, it is noted that the statelessness is already diminishing in the Internet to a certain extent due to ever-growing use of middle boxes that are largely stateful. The middle boxes are generally considered to compromise network transparency and break End-to-End (E2E) principle. Yet, in practice they bring a lot of value to commercial enterprises by performing Network Address Translation (NAT), firewall and similar functions.

The second goal *it should support, at the transport service level, a variety of types of services* manifested in to not making any underlying assumption about the services in the datagrams. Unfortunately, this behavior does not translate well in TCP/IP. In the context of telecommunications and data communications convergence, voice service in a telecom network outperforms Voice over IP (VoIP). Support for real-time applications needing low latency still cannot be assured. This is due to lack of service awareness about the packets as it is transmitted through the network. Clark had a broader view about the structure of datagrams as building blocks that provide pieces of information about services and corresponding resource requirements in such a manner that each datagram is a self-describing construct. This behavior rightfully, was too complex for that time and did not make it to TCP/IP. While Type Of Service (TOS) in IP is available, it is a) too generalized for emerging services characterization, b) in practice, the interpretation and scope is always within an internal network and has no significance in internetworking.

The third and seventh goals, '*the architecture must permit distributed management of its resources*' and '*it must be accountable'* are somewhat related to the cost. Distributed management of network resources is realized through control plane protocols. In this regard, the composition of services and allocation of network resources, has been a difficult problem. This is because of the trusted domain concept and establishment of trust between transit networks happens outside the Internet Protocol (IP). In the absence of seventh goal (accounting), there is no distributed way to convey explicit business value in datagrams to obtain resources from transiting networks. It would have been a simpler problem to solve if the structure of datagram had permitted for presence of accounting information. Hence, the third and seventh goals of original design have remained unfulfilled.

The fourth goal, *architecture must be cost effective* pertains to inefficiencies in packet transmission that are incurred either due to header overheads or retransmissions. In the context of IoT type of devices, large header related inefficiencies become even more prominent and are handled through header compression schemes [16]. Back then (1980s), a retransmission rate of 1 in 100 was tolerable. However, it is now unacceptable for AR/VR applications that tolerate loss of 1 in 10000 packets [17], using current TCP throughput computations for a 15200 Mbps stream with delay tolerance of 0.106 ms. For such applications, retransmissions and packet loss have to be absolutely avoided with the assumptions that end users are willing to incur the cost of sych services.

Essentially, many of Clark's goals are not sufficient to meet present-time service requirements as discussed in this section and a reformation of the design principles are necessary. This can possibly be achieved by reviving the concept of datagrams carrying relevant information for use in the networks. Emerging applications are in need of in-network state, service awareness and resource control. The cost effectiveness varies for different application environments and business demands. To this effect Internet being cost-effective cannot be a fundamental design goal and applications should have choice to opt for premium services.

V. Engineering Inertial Effects

Over multiple decades, a lot of engineering effort has gone into keeping the Internet stable and allowing it to scale. The resulting Internet is rigid, that resists changes necessary in the context of a wide variety of modern applications. The structure of the present day Internet can be described through a set of inertial effects since they provide means to maintain status quo while avoiding substantial changes. An exploration of these effects will reveal the trade-offs between their strengths and shortcomings which may further help design next-generation architectures.

A. Commercial Effect

Commercial aspect of the Internet manifested into three characteristics viz. explosion of routing table, proliferation of private networks through tunnels, and a surge in non-default forwarding of the traffic.

Firstly, as new websites or corporate sites are added, replaced or merged, the global routing table is affected and often misconfigured routes lead to the instability in Internet backbones. This can become a cause of major outages on regular basis [18]. To minimize global routing updates, techniques like damping [19] are employed. However, this method has limitations such as loss of connectivity due to suppression of correct updates, missing routes and the configuration complexity [20].

Secondly, commercialization also created a business case for multi-site private networks. It became necessary for any corporation to isolate and protect its digital assets when traversing through the public Internet. Interestingly, the original TCP/IP design was a single system with no notion of network-to-network communication. To implement private networks tunnels are deployed emulating a network as a host (through a tunnel endpoint). It then requires a complex instrumentation and an entirely independent stack of protocols [21].

Thirdly, the measurement studies in [22] and related work [23] discovered E2E path anomalies, i.e., not all packets between the same source and destination were subjected to the same path (non-default routing). This is because various commercial features and business reasons have different service requirements that are fulfilled by operator driven configurations and/or route-policies.

The inertial aspect of this effect is that the current architecture implicitly resists change of any kind in favor stability, overrides the notion of single system (through Virtual Private Networks (VPN)s) and overrides default routing. A variety of services requiring real-time, high bandwidth, zero packet loss etc. resort to tricks such as path computations, route policies and complex configurations just to get close to meeting their service level objectives. They take away the dynamic nature of forwarding which is not desirable traits of emerging applications where seamless connectivity and ubiquitous mobility are essential requirements.

B. Layering and E2E Effect

The layering principle is honored when a) separation of layers is not compromised or violated (layer independence), b) there exists minimal layer crossing (services provided to next higher layer only). The E2E principle creates transparency; i.e., the network bears no knowledge of the contents and remains non-discriminant about the applications. Both layering and E2E principles are the foundation of the Internet and a consequence of how TCP/IP got implemented.

Layering gets breached in the form of tunnels, overlays, NATs, etc. through port blocking or filtering techniques. It is well known that many in-production routers do not allow traffic other than TCP and UDP [24] to pass through. This is an obvious violation but is necessary for Internet Service Provider (ISP)s to protect their network against spurious attacks. Layering helps scale different type of services but there are a few drawbacks as well. Firstly, multiple levels of encapsulations lead to bloating of the proverbial narrow waist in hourglass structure of TCP/IP. Secondly, the encapsulated layer comes with its own protocol, control and corresponding management entities, thereby increasing network complexity.

From an architectural standpoint, layer abstraction is a powerful concept, but in practice, it has resulted into a mechanism to hide deficiencies in the structure of datagrams that do not carry sufficient control information. Similarly, E2E effect has manifested into dumb networks and intelligent end points making is impossible for networks to make informed decisions unless middleboxes are deployed.

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C. Network Ossification Effect

Ossification suggests both long-term survivability and as a consequence rigidity in the network. It is believed that both network [25] and transport [26] layers resist adoption of new technologies. The ossification is a consequence of gradual building of resiliency and stability in TCP/IP technology over a long period of time (also alluded to in Section V-A).

SDN has been positioned to mitigate effects of ossification and has produced several changes in network control through programmability. However, SDN also brings an increased complexity and scalability limitations due to central control for programming the networks. In contrast, transport ossification is mainly a side-effect of use of middle boxes to bypass lack of modularity in transport layer for service customizations. In an E2E client server communication, any change to TCP, needs coordination with all client instances. Over time, the structural uniformity has become more rigid and most customizations happen over HTTP instead (e.g., DASH, session management).

The ossification of both network and transport layer implies they cannot be changed. SDN only deals with the control plane programmability, however, dataplane flexibility is extremely desirable for M2M communications requiring low latencies. The emerging applications scenarios are exactly the kind where application level session management will be inefficient and impractical, instead a network assisted packet processing techniques will be necessary.

D. Addressing Effect

The Internet is ubiquitous and homogeneous because of a uniform network addressing scheme in which a host is understood in identical manner in each network. There are two major factors regarding host addresses. First factor pertained to the size; it was recognized that the 32-bit width will be too small to cover every host on the Internet [3] [27]. Second factor related to its structure limitations; that the early binding aspects of an application and address turned out to be limiting the functions of mobility, device portability and multi-homing. This is also characterzed as location and identifier separation concept.

E. Services Effect

Even though variety of services were anticipated in the architecture, the earlier ones were primarily texts or static digital image formats. With digitization of audio and video, many new applications started to emerge and Internet was suited for many of those. For example, early attempts to implement VoIP, which is a circuit-switched telecommunication service, over a packet switched network were suboptimal, because the goal of the internet was to support best-effort communication, but voice performs the best as a circuit switched application. The QoS markings that exists today are coarse-grained, therefore, only a very narrow category of services can be supported.

Today, there are even more variety of such services but with even more stringent requirements. M2M communications take humans out of the loop; an application relies on each machine-entity to function properly, respond, generate and process events according to prescribed behavior. Any delay, loss of packets in network could be misinterpreted as failures, causing system to take serious recovery actions leading to loss of productivity.

F. Summary of Inertial Effects

The runtime state of the Internet is a consequence of above mentioned effects that emerged from the TCP/IP implementation. Due to limitation of space, and non-technical aspects that vary for different countries, we do not discuss governance aspect here; however, it is also relevant in shaping the Internet. For interested reader we offer the following references [28] [29].

The Internet is 'robust yet fragile' [30]. It is well-engineered in responding to predicable events, but unable to handle unanticipated circumstances. Layering, addressing and commercialization effects are virtue of the principle of keeping network layer simple. The mechanisms adopted were mainly based on conservative and cost-effective design choices with the goal of scaling the Internet. Ironically, this has brought comlpexity elsewhere in management, operations and orchestration functions of the networks [31] [32]. In constrast, Ossification and services effects aimed to minimize variations in the network thereby lacking customization mechanisms that are needed for finer granularity of control for certain classes of applications.

The TCP/IP is an over simplified instance of the original design and trade-offs made several decades ago were well-suited for applications of that time. Not only that the state of art routers and network nodes are more powerful now but the networks play a much bigger role in all aspects. The emerging applications driven by M2M communications will expose the above mentioned limitation even further. A new balance has to be struck between preserving the stability aspect of the Internet and yet allow it to evolve for those applications.

VI. Properties for Transition from Classical to New Internet

We have discussed the architectural aging and engineering effects in previous sections and call the structure as classical Internet.

The Internet is diverifying in all facets, a new Internet architecture must be defined to be simultaneously public and private, secure and open, social and commercial as well as both human and machine centric. In the context of discussions in previous sections, the properties for new network architecture are proposed.

A. Multi-Instance Architecture

The idea of multi-instanced Internet should be explored. Where an instance could be a special purpose and means to connect with other instances if necessary. This could serve new generation of technologies with specific type of network resources better. This has already been noted as fragmented Internet in [33] (as a warning, not a feature). Often general-purpose solutions suffer from performance and complexity. In contrast special purpose networks can be more efficient but limited. A single system is automatically prone to be rigid and conservative, being a single point of failure. Having multiple instances allow features to be experimented and withdrawn.

RFC1958 [27] discusses the possibility of at least two network protocols to be in use to support gradual transition. Prevailing encapsulation-based mechanisms suffer from bloating (Section V-B). This approach could provide with flexible and dynamic bindings to information, in a tunnel-free manner.

B. Distributing Complexity

Section IV expains that the fate-sharing principle has led to stateless design of the networks. The connectivity scenarios are evolving rapidly as a large number of endhosts (e.g., wearables, sensors, appliances, etc.) are far less powerful than the routers and switches. It makes sense for network to be more aware of device behavior and the services they require by distributing some of communication processing from end-points into the networks. Several emerging applications (for example, V2X, industrial automation and remote control etc.) have strict service level criteria for normal operation in terms of bounded latency or committed bandwidth. Without direct sharing of such information, the network design becomes inefficient as an operator would need to understand requirements of each application and setup resources accordingly through central control on per hop basis. Also this is possible with SDN paradigm, maintenence of per flow state is non-trivial. In current architecture, the networks have evolved in a manner that the intelligence lies with the applications or end points. New design should identify mechanisms that distribute intelligence into the networks, as in service awareness, runtime state or behavior. This In effect, distributes complexity partially from the end points in the network. Such considerations are manadatory to meet service level objectives of absolute guarantes .

Many technological advances have happened in the hardware of network devices. The Network Processing Units (NPU)s, Ternary Content Addressable Memories (TCAM)s and port Application Specific Interface Circuit (ASIC)s are much faster than before. New architecture can use advances in hardware to their advantage while exploring solutions for emerging applications.

C. Self-Sufficing Datagrams

The datagram provides a basic building block out of which a various types of service can be implemented. The notion of a datagram carrying service-centric information can be an extremely powerful concept to address several control and management inefficiencies in network. A datagram should be a self-sufficient, self-describing entity comprising of user payload and control information about the flow or application it is part of. Obviously, it comes at a cost of additional bits on wire but a sensible structure and the framework could be deployed. The information must be network centric and should be detached from the transport aspects. As mentioned before, hardware advancements can be used to deploy efficient processing in the networks.

D. Flexible Address Structure

While the uniformity of addresses need to be preserved for the sake of reachability, a variable structure that is more sensitive for IoT devices should be supported. This has already been proposed in [34].

These are the main recommendations and can be used as guiding principles for new architectures to make distinction between the things in networks that should change (e.g., services, resources), and the things that provide stability (e.g., uniformity of addresses and layering). Other guidelines are possible based on specific choice of architectures but we only mention the ones that can be added to any next-generation architecture proposal.

VII. Factors Driving the need for New Internet

As mentioned earlier in Introduction, the need to change is driven by applications. Had the communications remained web-based online transactions or consuming streaming media, the current Internet works just fine. However, a ubiquity of connectivity is emerging in several aspects. It is required to think of the Internet as a fabric that interconnects humans, services, sensors, devices etc.

It is well known that IoT space will grow to billions of devices and each of them will have varying characteristics such as identity (corresponding connectivity address and gateway), its functionality (what purpose is it used for), energy efficiency (to help determine right type of transport mechanisms) to state a few. This high level of diversity is compounded by the volume of data that is produced at varying intervals. As a result current foundations of transport protocols do not apply to IoT, new techniques to efficiently transfer information and yet reducing or eliminating setup times are needed. 4

A fully automated vision of Industry 4.0 takes IoT to next level in terms of M2M communications. Today manifacturing networks are proprietory and purpose built. Looking ahead, there are three factors that will drive integration of Industrial network into mainstream Internet, a) combining Information Technology (IT) and Operation Technology (OT), b) use of common technologies, c) resource assurances. Even through the manufacturing in a factory is automated, OT and IT are managed as two separate networks. This requires a human to integrate results from information technologies in to operations. To achieve complete automation, IT and OT must be combined so that the results from complex analytics can be fed into command center. Secondly, the investments in infrastructure can be reduced by using standard technologies, which will not only incentivise manifactureres to automate at large scale but also allow with modern cloud based infrastructure solutions.

Inspite of the above compelling factors, it is a difficult task to change the incumbent Internet owing to its success. Today, it is so big that even minor outages are unacceptable. The Internet is IP based and most of the standardization is driven by Internet Engineering Task Force (IETF). These standards can only afford to bring segmented improvements in a particular focus area such as operations, routing, transport etc. Architectural changes related discussions often happen at other Standards and Development Organization (SDO)s such as European Telecommunications Standards Institute (ETSI), International Telecommunications Union (ITU) involved in study and evaluation of new network architectures. Perhaps a close coordination among these SDOs will be necessary to further the design of new architecture.

VIII. Conclusion

In this paper, we surveyed two related topics; first, the design decisions that led to current network architecture and were reasonable at that time. The second topic reflects upon the consequences of first in terms of its inertial effects that makes it difficult for the Internet to evolve from its current state. We also establish that the foundations of Internet architecture have been strong and were well engineered. However, in the context of emerging applications and new types of communications, some of the principles are outdated and must be revisited. This can be achieved either through a new or evolved architectural principles that balance both incumbant stability and adoption of new features. Looking ahead at emerging applications, Internet as a single system will be difficult to scale, it is simpler to evolve and adopt in multi instance environments. Finally, to future-proof new architecture and design, datagram building blocks are the key. They should be allowed to evolve, be extensible and support flexible mechansims for variety of applications.

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