Innovation, Verticals, and Beams: Importance of Time-Domain Mastery for 5G-and-Beyond

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Abstract

Mastery of the time domain is essential to achieving 5G-and-beyond innovations and effective beam control and management processes, as well as serving the needs of different industry verticals.

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1 Introduction

Through years of advancement, the wireless industry has become quite effective at frequency-domain management. But what about the time and spatial/beam-domains? Have we mastered them yet? 5G-and-beyond presents new synchronization problems that require new solutions.

The industry has not mastered control and management of the *time-domain*, at least not for 5G. Mastery of the *spatial domain*, however, does not exist even for 4G, though some progress has been made using implicit spatial domain management via power control, static cell/sector laydown and low rank MIMO. Trouble is, mastery in the spatial domain is essential to 5G effectiveness and efficiency.

Evolving from 2G to 4G, the industry has continually improved at managing our essential resource, the electromagnetic (EM) spectrum/frequencies, via mastery of the frequency domain. And we've done okay at managing the spectrum via time-domain techniques. Our time-domain schedulers have become more sophisticated and our time-and-phase-sync capabilities have improved at meeting the effectiveness and efficiency needs of 4G – even serving the *initial* phases of 5G NR as it applies to enhanced mobile broadband (eMBB). Note that the 5G eMBB application is essentially a souped-up version of the well-known 4G mobile broadband.

Still, 5G NR eMBB is predicated on the use of beams for spatial domain management. Moreover, bear in mind that eMBB is only one fairly generic piece of the 5G applications puzzle. Another factor is the many industry Verticals who will rely on emerging 5G Ultra-Reliable and Low-Latency Communication (URLLC) services. Further, the nature of innovation and evolution for the 5G architecture—as an overall system and ecosystem—is fundamentally changing. And it is doing so at an unprecedented pace.

Improved frequency-domain knowledge and localization correlates to improved time-domain knowledge and localization. These in turn correlate to improved localization in the spatial domain. This improvement enables multi-point internode coordination that is otherwise not feasible for the communication service... and for the time-stamped, time-ordered real-time global event sequencing knowledge that is required by critical applications using that service – as well as for innovation/evolution of the communications service itself.

Time-domain mastery depends greatly on effective synchronization – making sure events are ordered and aligned in time. Broadly speaking, the coordination provided by synchronization can be used to (A) *prevent* things from colliding into each other at a given moment or (B) ensure that things *do* come together at the same time. Examples of the former are vehicles at an intersection and the energy from wireless transmissions interfering with each other. Examples of the latter are meeting a friend for coffee and the energy from wireless transmissions in a directional beam forming antenna. Please see the "Vehicle Traffic Analogy" section at the end of this article for a story depicting many of the issues and solutions entailed in such coordination and synchronization.

2 Importance of Time Domain Mastery

Time Mastery for Innovation within 5G-and-Beyond

As innovation in 5G and beyond accelerates, Artificial Intelligence (AI), Machine Learning (ML), and computational intelligence are coming to the forefront. The integration of computational intelligence approaches in both the design-time and run-time in new systems depends heavily on deep integration and management of time and events into most every 5G system component – and upon exposing that shared time knowledge globally. Also central to new approaches are evolving mainstay processes for Fault-, Configuration-, Accounting-, Performance-, and Security management (FCAPS).

Real-time analytics and control applications tend to operate on the fly using streaming IoT and sensor time-series data/events. This behavior allows operators (and even consumers) to gain actionable insights. Significant advances are expected in our abilities to understand how things have been changing, to monitor how things are changing in-the-moment, to detect and resolve anomalies, and to forecast how things are likely to change in the future, as partially illustrated in Figure 1. That last item, forecasting change, is essential to moving from reactive to proactive network management and into real-time network management and control.

Real-time low-latency streaming of events (e.g., I&Q—In-phase & Quadrature— symbols) are already an inherent aspect of communications

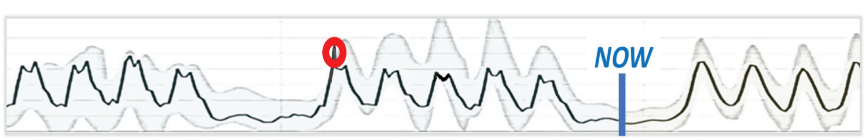

Figure 1 A time series of historic observations can be used to detect anomalies and predict future events.

and physical-world sensor signal processing. These time-stamped events may take the form of streamed event logs. They are also a prerequisite for several valuable approaches: real-time time-series analysis; on-the-fly ML for pattern recognition; real-time anomaly detection; predictive analytics; and prescriptive closed-loop control techniques.

Ordering and time-stamping are key to innovation. This is because both open-loop and closed-loop learning and control—whether by traditional or leading-edge computational intelligence methods—are no longer just another option to speed system innovation. In fact, they are now essential table stakes. Consider the rapidly increasing *dynamic* complexity of our wireless systems along with their already significant *detail* complexity. These contribute to difficult to understand non-linear and emergent behavior of the system that is increasingly difficult for us to even conceptualize. Effectively controlling, evolving, and innovating upon that system is all the more daunting.

This complexity is why global standards—such as from 3GPP, O-RAN, and others—are about much more than simply lowering Total CapEx and OpEx to increase overall profits.

The majority consensus has become that we need to be about exposing every component of our emerging 5G and beyond-5G systems in a composable, Lego-like fashion. Systems need to be configurable via "levers and knobs" by our network management systems—both standardized as well as the innovative value-added aspects. The controls can then be adjusted as necessary to achieve desired effectiveness and efficiency goals by SON and higher-level controllers – as are being developed, for example, in private labs, 3GPP RAN and SA5 standards WGs, O-RAN WGs and Open Network Automation Platform (ONAP) WGs.

Without such exposure and related control, it seems unreasonable to expect future "Industry 4.0" and other critical communications systems to be effective at consistently delivering the required QoS, security, and reliability.

Time Mastery for 5G-and-Beyond Verticals

> "5G will be the central nervous system in the factory of the future."
>
> – Andreas Müller
> Bosch researcher and chairman of the 5G Alliance
> for Connected Industries and Automation (5G-ACIA).

Enhanced Mobile Broadband (eMBB) is one thing. Verticals can certainly benefit from eMBB as it supports the traditional *Information* Technology (IT) networks industry, and consumers, have become accustomed to it. However,

Figure 2 Critical Vertical Applications.

new value creation for critical verticals lies mostly in enablement of their *Operational* Technology (OT) and OT networks.

For *critical* OT, the relevant new use cases rely on 5G Ultra Reliable and Low-Latency Communication (URLLC) application services. Here, the larger challenge is the demanding nature of interacting with the real physical world (sensing and control) and the increased risks associated with these URLLC-based applications, such as those leveraging emerging 5G New Radio-Industrial Internet of Things (NR-IIoT) capabilities. Consider – as illustrated in Figure 2 – the possible use cases: functional safety, autonomous transportation, medical, "Industry 4.0", or other critical monitoring and control use cases. All of these entail significant consequences for poor performance or unexpected behavior; hence, the requirements on safety, security, and reliability are extremely high.

Just as with innovation within our 5G-and-Beyond architecture and systems, effective usage of the URRLC communications by industry verticals *requires time-domain mastery*. Critical verticals are targeting an approximate $+/-1$ μs Time Alignment Error (TAE) requirement, which is only in the realm of high accuracy sync services.

What constitutes "high performance" goes beyond high accuracy. Time-sync service reliability and availability matter as well. This is in part due to TDD channel reciprocity benefits for 3GPP 5G NR Frequency Range 2 (FR2) mmWave beam forming. Here, TDD implementations will be predominant unlike in 4G LTE, which tends to be mostly FDD. With TDD, if the time service is lost—whether current "4G quality" sync or new high-accuracy sync—a TDD 5G NR cell would likely suffer degradation in handover and intercell interference coordination within perhaps 24 hours of, say, GNSS/GPS service loss (should a backup time service not be available).

Global enterprises must work with more than one operator. Within a single operator, it is already difficult to offer high-performance/high-accuracy time sync services based on physical-clocks. Where multiple operators collaborate to serve these enterprises, the difficulty is still greater. Certain approaches can help alleviate this problem. Consider a distributed hybrid logical/physical clock implementation, where nodes in a network system share a fine-grained global knowledge of the logical sequence of events. This can provide time sync closer to the actual physical clock time, even across administrative domains. This improves ordering and time stamping in the face of less-well-synchronized/higher TAE multi-operator environments. This approach should prove to be a promising avenue for further technical development and cross-operator standards development.

To date, basic time-and-phase-sync services have sufficed for up-to-4G purposes.

But our "good-enough for 4G" not-bad time-domain management and sync services are no longer sufficient. Improving time-domain mastery for new critical use cases will require much higher performance solutions.

(Interesting to reflect on progress: London's Big Ben clock was an acceptable enough time service to help keep the first Industrial Revolution in sync. Before that innovation, the simple ringing of a bell was all it took to coordinate the agrarian communities going out into the fields in the morning and coming back in time for meals.)

Time Mastery and Intelligent Beam Management are the Solution to 5G's Spatial Domain Beamforming Challenges

In existing technologies, frequency channels are added to allow for more traffic. Emerging beamforming technology has a similar effect, but instead of adding new frequency channels, it applies different technical mechanisms to enable improved traffic flow. While essential, adding brand new frequencies can often be slow and expensive, subject to auctions and other allocation methods, differing global regulation, and requiring emerging technical improvements. In contrast, adding new traffic beams for a given frequency can be done somewhat instantaneously, using an Intelligent Beam Management System (IBMS) to ensure effective operation.

Beamforming antenna subsystems are already available and making increasing inroads in deployments. Advanced versions offer improved Signal-to-Noise Ratio (SNR) as well as on-the-fly reconfigurability to optimize SNR for, say, coverage, capacity, reliability, or energy conservation. A cellular carrier may choose which figures of merit to optimize per their unique overall business model – or even per moment-to-moment priorities of their customers and profitability to the carrier.

After carriers have placed their beamformer hardware, the equipment must be managed individually and as a collective whole of multiple cells by an IBMS. In this schema, parts of the intelligence and decision making can be managed at the extreme edge—the antenna system itself—for low-latency local transmission/reception point optimizations.

Conversely, part of the intelligence and decision making is centralized for overall global optimization of those various remote beamforming antennas. The centralized and distributed AI and ML control loops work together in a hybrid fashion. In an IBMS for example, large scale resource-intensive neural network training and optimization may be performed centrally, while *low-latency* inference, lightweight training, and control decisions may be performed at the antenna itself.

One challenge with the current 4G-centric time-sync approach and its accuracy relates to the 5G eMBB application itself. That is, eMBB requires effective beamforming, which in turn requires improved time-sync. This is an essential requirement for effective and efficient multi-cell beamforming like that managed by an IBMS.

A key approach to meeting the capacity needs for eMBB is moving to higher frequencies like 3GPP 5G NR FR2 where there is more spectrum available. These higher frequencies require the efficiency benefits of beamforming, beam steering, and management to offset the related increased propagation and coverage challenges. 5G is definitely beam-centric. And in industry practice, beams (essentially, energy directed in space) are still somewhat new to our engineering and operator worlds.

We have an attendant need to significantly improve our *explicit* management and control of this spatial domain. In 4G to date, we have survived via *implicit* spatial domain management through various forms of power management and mostly static design-time rather than run-time cell laydown and cell sector planning. With 4G you can use digital signal processing to deal with the time/frequency and spatial domains for the most part separately. Now, with 5G beamforming, all of these concerns can be addressed together – as they should be for optimized carrier operations.

IBMS-style simultaneous management and control of the spatial domain and time-domain has become critically necessary. Mastery of the spatial domain is needed; mere best-effort management is not enough. And with multiple cells working in harmony, spatial domain mastery is directly dependent on mastery of the time-domain. That combination is a new problem.

Practical Use Cases from the Wireless Comms World

Multiple emergent concerns around beams and innovation come together in our own "wireless comms vertical" at the RAN fronthaul. It is helpful to consider the use case of mobile fronthaul as well as its place in time/phase sync service delivery and internode beam management. Mobile fronthaul is the transport network between a baseband controller and one or more Remote Radio Head/Beamforming Antenna System units. For example, in an O-RAN-based architecture this would be the transport network between the O-RAN Distributed Unit (O-DU) and one or more O-RAN Radio Units (O-RU's). This use case is also a good microcosm-example of the larger challenge of how to effectively manage and innovate within our communications system.

Solutions to conquer (control/manage/schedule) the spatial domain are generally either constrained or enabled by the underlying fronthaul, as well as by the Advanced Internode Coordination functions that may operate over that fronthaul. Hence, the fronthaul's performance is also an urgent problem to solve, in that fronthaul must first conquer and manage the shared knowledge and synchronization of time and phase in order to allow improved management of the spatial domain.

Small cells are proliferating, and network densification is increasing dramatically due to FR2, topography, indoor usage, etc. Therefore the sheer number of cell edges—and increased total aggregate length of cell edge—increases the ratio of edge coverage to non-edge coverage across the entire system. This ratio change is driving a higher percentage of UEs and end-systems into operation within the cell edge rather than within the cell/sector centers. So the intercell-interference (co-channel, in-band, & OOB) is becoming a bigger issue than current time-domain scheduling and internode coordination techniques (eICIC/feICIC, ABS, SON, etc.) can handle well. *Advanced* Coordinated Multipoint (CoMP) techniques are more than just these and further increase the design challenge.

Current and emerging advanced CoMP techniques require the spatial domain be explicitly managed and managed well. Doing so requires not only simple deconfliction and coordination of different beams across multiple nodes—a beam-SON/IBMS—but also leveraging those nodes to explicitly work together for joint coherent beamforming—an advanced beam-SON/IBMS.

Coherent, distributed beam forming is effectively a geo-distributed sparse antenna array jointly forming, steering, and managing beams. Such a system requires a fronthaul that can provide the necessary levels of low-latency, determinism, and synchronized internode communications. And *that* requires high accuracy time-and-phase sync in and across the fronthaul of $\sim +/-10$ ns Time Alignment Error (TAE) or better.

Of note, a less demanding though still improved sync accuracy will be needed for 5G NR Integrated Access and Backhaul (IAB) nodes. IAB and its wireless multi-hop self-backhauling is a critical capability of the 5G NR RAN, and accurate time must be fanned out to the IAB nodes. This need will only become more challenging when the IAB nodes themselves eventually become mobile.

As a bonus in the new approach, improved, high accuracy sync capability *also* happens to allow improvement to the existing more traditional time-domain scheduling for intercell interference management.

Figures 3 and 4 portray an example of the problem that will be resolved: Time alignment errors causing TDD time slot and frame start misalignment and interference. In this scenario, the TDD guard periods are misaligned, causing gNB B to transmit in its Downlink at the same time—and interfering with–gNB A's UE Uplink transmissions. General time/phase alignment error impacts also come into play in a somewhat similar fashion when synchronizing beams—coherently or not—from multiple transmission points or gNBs.

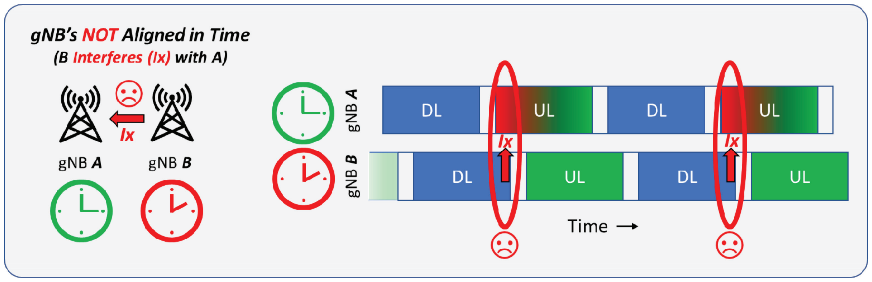

Figure 3 gNB's Not Aligned in Time.

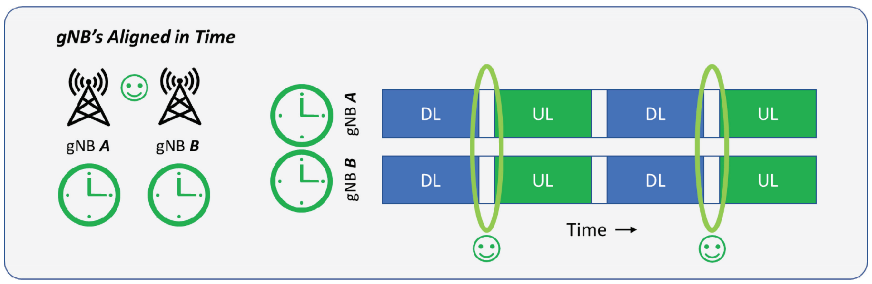

Figure 4 gNB's Aligned in Time.

3 Industry Standards and Ecosystem Efforts: New Time-Phase Solutions

As an industry, getting to these high-performance time-phase sync solutions will certainly be achievable, although it will not be easy. Sync is a challenging area and we can leverage much of the work already completed and still underway. The topic is quite broad, with numerous options, parameters, and implementation choices. Practical resolution requires the establishment of specific *profiles* of existing and emerging sync service standards to fit them to 5G NR and 5G mobile fronthaul needs. Further, ideally, we would also establish a 5G-specific profile for the *OAM* of those underlying 5G NR and fronthaul sync service profiles.

The following reflects the thoughts/opinion of the article authors and not necessarily the position of 3GPP or other SDOs:

Industry standards organizations may want to consider several new profiles: 3GPP RAN WGs for the service profile itself and 3GPP SA5 (responsible for 3GPP Telecom Management) for the critical sync management profile.

This work could potentially be done in conjunction with the O-RAN Alliance. As these groups represent the users of these wireless telco 5G sync services and so are close to the need, they seem to be appropriate forums and they have effective mechanisms for undertaking these profiling efforts. Industry vertical SDOs in automotive (5G Automotive Association, 5GAA) and industrial internet (5G Alliance for Connected Industries and Automation, 5G-ACIA) could contribute directly via members or via liaison to these 3GPP and O-RAN efforts. The results could then be communicated to the ongoing ITU time/phase and 3GPP time/phase standardization efforts, IEEE, ATIS, and others – and further iterated via normal inter-SDO liaison mechanisms.

It is worth noting that within 3GPP, SA5 is well suited as a focal point for inter-SDO sync OAM collaboration, as they or their members already interact with the ONAP effort, which is part of the open source Linux Foundation, the O-RAN Alliance, 3GPP itself, and others. Further, as OAM is SA5's 3GPP mission, this remit does seem to include OAM for sync services consumed as well as those delivered by 3GPP-based wireless communications systems.

While the theory of all this may seem relatively easy, the development of effective, practical, well-managed systems for sync will require significant coordinated effort. The problem is challenging enough—and the opportunity big enough—that it will draw upon much more than SDO efforts to drive the success of the new sync solutions into our industry. The coordinated involvement of R&D Lab studies, POCs, interop/test fests, field trials, and open source initiatives will all be needed for meaningful success.

Vehicle Traffic Analogy

A not unreasonable analogy to wireless communications is vehicle traffic. Synchronization, coordination, collision, rendezvous, and innovation-enablement come into play. "Lanes" in a road are roughly analogous to bandwidth in frequency "channels", as can be beams. So, let's follow "Bob" on a drive he finds important:

> *Bob was excited as he and Alice agreed to meet at the grand old train station in the center of the city to catch the train together to the little Italian restaurant in the small town where they once met. Unfortunately, there's only one daily train, Bob's office is in*

the suburbs, and his meeting with the company's biggest customer ran over. As he made his way through traffic on one of the two-lane two-way streets towards the train station, Bob unfortunately kept having to stop at poorly-synchronized red lights and he realized he'd likely miss the rendezvous with Alice to catch the train by at least 10 minutes if he didn't do something quickly.

Fortunately, Bob had lived in the city for over a decade and knew there was a four-lane two-way street a couple of blocks over that supported much more traffic.

He headed over there and the pace picked up noticeably. Bob checked the ETA on his smart phone. Unfortunately, while the wider four-lane avenue was faster, it was not enough. He was still running a few minutes late.

Fortunately, Bob remembered his friend Joe—a planner in the city's department of transportation—had told him that they'd made some upgrades to the lights on 6th Avenue to improve their time-synchronization so that many if not most drivers encountered a string of green lights as they drove 6th. Bob cut over to 6th and sure enough traffic was flowing smoothly for blocks. Unfortunately, just as he was beginning to relax, Bob watched as two cars collided in the intersection up ahead. The traffic lights were entirely off. Likely another problem with the city's old power grid again. Tightly-synchronized or not, if traffic lights are completely unavailable to coordinate an orderly vehicle flow through intersections, cars may undesirably meet in the same place and time. The clock was ticking, and he imagined Alice's hurt expression as she stood alone on the platform watching the train leave without them.

Bob was getting desperate. While he figured he was grasping at straws, Bob decided to call Joe to see if he might have any advice. Fortunately, Joe did. Joe noted the city was trialing an innovative new predictive traffic analysis system in another part of the city not that far from Bob's current location, and the power was still working in that sector. Bob, harried and more brusque than usual, was skeptical. "I've been driving in this city for a decade Joe, and that's the worst traffic in town."

"WAS, buddy. Was.", Joe replied. "That's why we're trialing new solutions. It works like this: First, we upgraded all the clocks on the traffic lights and cameras in the area. Before, the time-stamps they sent in weren't precise and traffic measurements came in out of order and with uncertain timing. With no idea which events were truly happening before other events, our experts—as well as our new AI software we're testing—were simply unable to detect a pattern in the traffic flow, predict where high or low traffic density was about to occur, and how that traffic would impact adjacent neighborhoods. One local light or two might be doing its job fine, though the global traffic picture was entirely clouded. Second—with the better clocks in place—we turned on the enhanced AI software and it allowed us to not only see and predict, but also prevent many of the traffic jams. I tell you Bob, I've saved so much time on my commute through there that I actually have time to pick up the kids from school a few times a week now." Surprised and happy, Bob wheeled his car over to the upgraded part of the city and sure enough, he was able to drive the speed limit, hit only a few red lights, and rendezvous with Alice at the train station. They were both in just the right place and time to catch their train, enjoy dinner with an amazing view, and have an excellent evening.

Biographies

Colby Harper, CEO, Pathfinder Wireless. Colby has led strategic wireless innovation, early and late-stage R&D, and operations since the 2G era, including hands-on design of novel high-performance synchronization and advanced wireless systems. A specialist in adaptive real-time control of complex systems, Colby has served as a founding member of international standards organizations and initiatives and contributed to telecommunications policy legislation. He is a GSMA Vendor Technical Partner, AAAI member, and active in SDO's including 3GPP, IEEE, O-RAN, and WInnForum CBRS, with a focus on their intersection with the global wireless R&D ecosystem and spectrum regulatory landscape. He received his BA in Economics and Certificate in International Economics from the University of Washington.

Brian Deutsch, CEO, Pivotal Commware. Brian was the founding CEO of Wavtrace, a broadband wireless equipment provider acquired by Harris Corporation (HRS) in 2000. More recently, he served as turnaround CEO at ApertoNetworks and EVP at BSQUARE (BSQR). Brian spent six years with Motorola, worked for NASA at Kennedy Space Center, was a finalist for Inc. magazine's "Entrepreneur of the Year," and has been awarded many U.S. patents. Brian has both actively contributed to and led industry and teams in emerging wireless standards efforts since the 2G era, including most recently 3GPP and O-RAN oriented teams. He received his BS in Electrical Engineering from the University of Miami.