# Directly/Indirectly Coupled Impact of Energy Constraints on Information-Control Connectivity in Mobile Cyber Physical System (m-CPS)

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Mobile cyber physical system (m-CPS) is a field that has gained significant momentum with application domains varying widely from next generation land, air, and naval transportation (e.g., hybrid electric vehicles (HEVs), more electric aircrafts (MEAs), unmanned underwater vehicles (UUVs)) to robotic swarms. Among others, a fundamental connectivity that exists in m-CPS is the one between energy and information-control connectivity. Unlike energy based infrastructures such as power grid or microgrid, which has sustained source of energy, m-CPS applications typically have a finite and constrained source of energy. So, in m-CPS, while on one hand, the connectivity of the physical system via the cyber layer provides the much needed distributed intelligence and adaptability, the extent of this feasibility depends for several applications on the finiteness of the energy itself. What is even more interesting is that this dependency of control-information connectivity on energy is some cases indirectly coupled while in others the coupling is direct. For instance, in several m-CPS applications, the cyber-control connectivity is dependent on a finite source of energy to support the cyber-layer connectivity and functionality. However, there are several m-CPS applications where this control-communication connectivity is through the same medium that also supports the connectivity for energy transfer. A review of the m-CPS literature appears to demonstrate that is interplay between energy and cyber-control connectivity has received limited attention. We discuss below a few of these important and emerging m-CPS research issues.

To begin with, let us consider the energy transfer from one-to-many or many-to-one or many-to-many mobile nodes. Such an application could, for instance, encompass robotic swarms or a vehicle-to-vehicle (V2V) energy-transfer application. Typically, in such applications, the medium of energy transfer in untethered and so is the medium for supporting cyber-control connectivity. We argue that the dynamic network throughput and the capacity limits of such a wireless-actuation-and-sensing network (WASN) is dependent on the volume of data as well as energy-packet transfer and cannot be determined using a sums-of-parts approach. For instance, if one wants to reduce the charging time, then, either the frequency of energy-packet transfer or the intensity of the energy packet or both needs to be enhanced. This will have a direct impact on the reliability of spatial-data transfer in the adjoining mobile nodes. So, a fundamental question is what is the optimal mechanism for co-transfer of energy and information given finite channel capacity and varying channel length? Yet another fundamental question is what is the capacity of the cyber-energy layer for a given task requirement and given distributed channel condition?

In the context of vehicular electrification, even though the energy-storage device is the mainstay for cyber-control, the same device also serves a dual purpose of supporting the vehicular mobility. Current research has clearly illustrated that the durability of battery, which has a direct impact on its serviceable life of the system, is directly related to the demand profile to which the energy-storage device of the vehicle is subjected to. Thus, an interesting cyber-control challenge for the m-CPS application is to define application profile for the vehicle or collection of vehicles depending for instance of the dynamic state of charge (SOC) of the energy-storage device. In yet another interesting innovation, the path planning for vehicle between source and destination can also determined based on this approach. One can think of this approach as a graceful transition from nominal to critical operation using event-driven cyber-control guided by physics of SOC estimate of the energy source. So, the extent to which the cyber connectivity can be ensured, which depends on the life of the energy-storage device, is in itself indirectly dependent on how the demand profile for the energy source is synthesized. It turns out that apart from land transportation vehicles, such a critical necessity exists even in battery driven unmanned underwater or unmanned aerial vehicles. So, the research need is pervasive aide from being a relatively new.

Yet another interesting application domain of m-CPS is the electrical railway smart grid. This is an area that has vast importance world-wide and is gaining momentum even in the United States. Currently, the approach to railway electrification is through spatially-distributed substations that ensure a continuity of power flow for the spatially distributed assembly of electric trains. Currently, the localized power demand is met by the substation with geographical proximity to the electrical locomotive. Unfortunately, this yields higher installed-capacity requirement for the substation for a given distribution of average demand since the dynamic power management is not spatio-temporally enabled. This has implications on cost as well energy surety since inspite of scheduling it is not always possible to ensure a spatio-temporal symmetry in demand distribution. So, an interesting and unresolved research in this domain of electrical m-CPS is to devise mechanism to integrate the electrical transportation physical layer to a cyber-control layer using the very power line that links the substation to the electrical locomotive to yield system optimization for higher efficiency, dynamic allocation of generation capacity, and dynamic change of spatio-temporal demand scheduling for optimal power flow. With regard to the cyber layer what is interesting with the communication over the power line as compared to the traditional power-line communication (PLC) is that spatial intermittent disruption of the pantograph of a train also creates a momentary disruption in information flow. Thus, resiliency of the cyber control needs to be ensured in the presence of spatio-temporal channel disruptions.

A final research direction is the need to synthesize mechanisms to resolve the unintentional interaction between the energy and cyber spectrums in several m-CPS applications to yield resilience. For instance, in the next-generation power-by-wire aircrafts, the power system is electrical supported by high-frequency solid-state electronics actuators that generate high-intensity electromagnetic interference (EMI) waves depending on the power functionality being executed. These EMI waves can interfere with the weak-strength communication electromagnetic waves that are used to support the aircraft as part of a mobile ad-hoc network (MANET). This non-cooperative scenario of the power-by-wire aircraft m-CPS needs to be dynamically resolved. For instance, given an energy-actuation profile, is there an optimal waveguide that can support the cyber-control layer connectivity with maximum robustness and throughput? Similarly, for a given cyber-layer connectivity mechanism and status, is there an optimal energy-actuation scheduling and functional prioritization that maximize data reliability and throughput? Needless to say, this is not a static-optimization but a dynamic-optimization problem based on condition-based monitoring of the cyber-physical layers.