

A SURVEY ON CONTROL UNDER COMMUNICATION CONSTRAINTS

Abstract—This paper is specifically written for the benefit of control and communication community and particularly to enlighten the communication community about the problems the control engineers are facing in today's world. Emphasizing the communications constraints for the control problems is the main idea of this paper. In this paper we discuss the outcome of our survey on recent results in Control under Communication Constraints (CCC). The results surveyed address the channel limitations in terms of packet rates, sampling, network delay and packet dropouts along with the problems faced by the control community and also the possible solutions in the light of convergence of Control Theory, Information Theory and Communications Theory along with Estimation Theory.

Keywords: Control under communication constraints (CCC), distributed systems, networked control systems (NCS), wireless networked embedded systems, estimation

I. INTRODUCTION

In modern cars and airplanes, as well as in networked homes and office buildings, modern control systems are increasingly incorporating communication networks in feedback loops. As most of the power plants and power systems are interconnected through the intra-national, international and regional grids, there is a significant role of information technology, communication technology and control engineering in efficiently managing the system as a whole due to increased complexity of the system. Wide use of sensors, actuators and controllers along with softwares and various types of communication equipments and networks is now a must for proper management of power plants and systems. Control engineers are thus forced to expand their application domain by incorporating the communication infrastructure into their designs, and by considering the impact of link capacity, latency, and packet-loss (which are collectively called communication constraints) on the performance of feedback control systems. In this paper the focus is on the control under communication constraints.

It has been suggested [1] by Sanjoy Mitter many times that a unified view of Control and Communication is badly needed if progress has to be made towards a science of distributed systems, where subsystems are linked via Communication channel. Control engineers must master computer and software technologies to be able to build the systems of the future, and software engineers need to use control concepts to master the ever-increasing complexity of computing systems. Networked Control Systems (NCS) are systems whose sensors, actuators, estimator units, and control units are connected through shared communication networks. Unlike regular control systems, in networked control systems the synchronization between different sensors, actuators and control units is not guaranteed. Furthermore, there is no guarantee for zero delay or even constant delay in sending information from sensors to the control units and control signals from the control units to

the actuators. When there is congestion in the communication network, some packets are dropped to either reduce the queue size in the path or to inform the senders to reduce their transmission rates. In real-time systems, particularly control systems, delays or dropped packets may be catastrophic and may cause instability in the control system. In this paper the survey results of a number of technical papers (mostly IEEE based) are presented particularly focusing on Control under Communication Constraints. This paper is organized as follows: Section-II is dedicated to discussion of papers on related work followed by section-III the conclusion and finally the reference.

II. DISCUSSION ON RELATED WORK

In paper [2] Babak Azimi-Sadjadi used the uncertainty threshold principle to show that under certain conditions there is a rate for dropped packets for which an undisturbed networked control system is mean square stable. Wireless networked embedded systems are becoming increasingly important in a wide area of technical fields. The vision of the European Project: Reconfigurable Ubiquitous Networked Embedded Systems (RUNES) is to enable the creation of large scale, widely distributed, heterogeneous networked embedded systems that inter-operate and adapt to their environments. The paper [3] by Karl-Erik Arzen, highlights how the complexity of the closed-loop system is increased, due to additional disturbances introduced by the communication system: additional delays, jitter, data rate limitations, packet losses etc. In paper [4] Sekhar Tatikonda and Mitter generalized the framework by applying traditional information theoretic tools of source coding and channel coding to the problem and presented a general necessary condition for observability and stabilizability for a large class of communication channels. It is studied sufficiency conditions for Internet-like channels that suffer erasures. In paper [5] Tatikonda and Mitter emphasized that there is an increasing interest in studying control systems employing multiple sensors and actuators that are geographically distributed. Communication is an important component of these distributed and networked control systems. Hence, there is a need to understand the interactions between the control components and the communication components of the distributed system. Here a control problem is formulated with a communication channel connecting the sensor to the controller and designed the channel encoder and channel decoder along with the controller to achieve different control objectives. Also provided here are the upper and lower bounds on the channel rate required to achieve these different control objectives. Specifically it is shown that a necessary condition on the rate for asymptotic observability and asymptotic stabilizability in a linear, discrete-time system is $\mathbf{R} \geq \sum_{\lambda(\mathbf{A})} \max\{0, \log |\lambda(\mathbf{A})|\}$ where $\lambda(\mathbf{A})$ denotes the

eigenvalues of the system matrix \mathbf{A} and \mathbf{R} denotes the bit rate without error. Typical communication channels are noisy and have delays. A complete understanding of the interaction between control and communication will need to use tools from both control theory and information theory. In paper [6] Yang, Tatikonda et al. showed that for a stationary additive Gaussian-noise channel with a rational noise power spectrum of a finite-order \mathbf{L} , two new results were derived for the feedback capacity under an average channel input power constraint. First, they showed that a very simple feedback-dependent GaussMarkov source achieves the feedback capacity, and that Kalman-Bucy filtering is optimal for processing the feedback. Second, they derived the explicit maximal information rate for stationary feedback-dependent sources. The authors in article [7] have explored the information flows associated with continuous-time Kalman-Bucy filters, and connected them with the entropy flows occurring in non-equilibrium statistical mechanical systems. It has been shown via a physical analogy that a law of non-decrease of entropy need not apply to such systems in the presence of observations that continue to supply new information. Like other Bayesian filters, the Kalman-Bucy filter is information conserving in the manner described in [8], and, because of this, it is also entropically efficient in the physical analogy: it achieves the maximum possible reduction in entropy from a given supply of observations, and stores no more information than is strictly necessary to do this. In paper [9] Tatikonda, Mitter and Sahai examined linear stochastic control systems when there is a communication channel connecting the sensor to the controller. The problem consists of designing the channel encoder and decoder as well as the controller to satisfy some given control objectives. In particular the role of communication on the classical LQG problem was examined. Conditions were given under which the classical separation property between estimation and control holds and the certainty equivalent control law is optimal. It was then presented the sequential rate distortion framework and bounds on the achievable performance. Inherent tradeoffs between control and communication costs were depicted here. In particular it was showed that optimal quadratic cost decomposes into two terms: a full knowledge cost and a sequential rate distortion cost. In [14] A. V. Savkin addresses the stabilization problem involving communication errors and capacity constraints. Unlike the classic theory, the sensor signals are transmitted to the controller over a noisy digital link. How much the capacity of this link should be in order that the stabilization be possible? Main result states that the boundary of the almost sure (a.s.) stabilizability domain is given by the channel zero-error capacity i.e. error-free capacity of the Channel. Capability of the noisy channel to serve almost sure (a.s) stability is identical to exactly its capability to communicate information with no error. Also, shown in this paper is the perfect transmission of as much information as desired can be arranged from the controller to the sensor by means of control actions upon the plant without violating the main objective of keeping the stabilization error a.s. bounded. Here, m th moment stability is considered with larger m means larger errors occur more

rarely. The tightest data rate bounds above which stabilization of a linear plant is possible were established for noiseless finite alphabet channels in both stochastic and deterministic settings. For stochastic problem setup, stabilization with respect to the m th moment was examined. Control signals can be employed as carriers of apriori prespecified information from the controller to the sensor. In paper [15] Matveev and Savkin studied observability /stabilizability of linear unstable systems over channels, which may lose messages. He followed the natural approach aimed at making the observation/ stabilization error small along any (or almost any) trajectory. The main result of this paper means that the plant cannot be stabilized or observed with a non-zero probability. More precisely, arbitrarily large stabilization/observation errors unavoidably occur sooner or later, even if the plant disturbances are almost surely, arbitrarily, and uniformly small. A possible conclusion from these facts is that in face both plant noises and packet losses, trajectory-wise observability / stabilizability appears to be too strong property, and weaker ones seem to be more relevant. It should also be remarked that considerations are given to channels for which the number of successive packet losses is not limited. If this number is limited, the above conclusion on nonobservability and unstabilizability does not hold. The paper [12] by Matveev and Savkin addresses a state estimation problem involving bit-rate communication capacity constraints. A discrete-time partially observed linear system is studied. Unlike the classic theory, the sensor signals are transmitted to the estimator over a noisy digital communication channel. A recursive coder-decoder state estimation scheme is proposed and investigated. It is shown that the classic Shannons noisy channel capacity constitutes the border separating the cases where the reliable state-estimation is and, respectively, is not possible with arbitrarily high probability. Thus the inequality $\mathbf{c} \geq \mathbf{h}(\mathbf{A})$ is sufficient and almost necessary for the system to be detectable via the noisy communication channel. Feedback in communication between the coder and decoder enables one to ensure an almost sure tracking. In [14] a simple distributed power control algorithm for communication systems with mobile users and unknown time-varying link gains is proposed and it is proved that the proposed algorithm is exponentially converging. Furthermore, it was shown that the algorithm significantly outperforms the well-known Foschini and Miljanic algorithm in the case of quickly moving mobile users. The main goal is to minimize power expenditure under the constraint that each user is provided with an acceptable connection to all relevant base stations. In [15] on Feedback stabilization of discrete-time linear systems with multiple sensors, controllers, and actuators, by Matveev and Savkin in CDC and ECC 2005, information is transmitted between them via a limited capacity deterministic communication network with arbitrary topology, which may be dynamically changed by nodes authorized to switch channels. Transferred messages may be delayed, corrupted or even lost; they may interfere and collide with each other. It is shown that the criterion for stabilizability is given by the network rate region, which answers to the question: how much information can be re-

liably transmitted from one set of points to another set of points. System is stabilizable if and only if a certain vector characterizing its rate of instability in the open-loop lies in the interior of the rate domain. In general, the rate domain of the primal network is not relevant here and a certain extension of the network should be employed. Furthermore, the relevant rate domain corresponds to a special subclass of decoders. In some cases, all decoders can be considered and this domain equals the standard one. In [13] by Matveev and Savkin addresses feedback stabilization problems in a remote control setup, where the measurements are communicated to the controller over a noisy digital channel. A discrete-time partially observed time-invariant linear systems are studied. It is shown that the classic Shannon's noisy channel capacity constitutes the border separating the cases where the plant can and, respectively, cannot be feedback stabilized almost surely. A quantized feedback control law stabilizing the system almost surely is proposed. The paper [16] considers a state estimation problem for a linear continuous-time system via a limited capacity communication channel. The observation must be coded and transmitted via a limited capacity digital communication channel. A recursive coder-decoder state estimation scheme is proposed and investigated here. A Deterministic interpretation of Kalman filtering is presented. This problem is motivated by the fact that many problems of control via a limited capacity channel mentioned above could be solved if a suitable estimate of the state was available to the controller. In the paper [17] Malyavej, Savkin et al. consider a state estimation problem for a continuous-time uncertain system via a digital communication channel with bit-rate constraints. The estimated state must be quantized, coded and transmitted via a limited capacity digital communication channel. Optimal and suboptimal recursive coder-decoder state estimation schemes are proposed and investigated. In paper [18] Matveev, Savkin et al. studied a linear discrete-time partially observed system perturbed by white noises. The observations are transmitted to the estimator via communication channels with irregular transmission times. Various measurement signals and even parts of a given sensor output may incur independent delays; messages transferred via the channels may be lost or corrupted. The minimum variance state estimation problem is solved. It is shown that the proposed state estimator is exponentially stable under natural assumptions. Nicola Elia has shown in [19] a general equivalence between feedback stabilization through an analog communication channel and a communication scheme based on feedback which is a generalization of that of Schalkwijk and Kailath. It is also showed that the achievable transmission rate of the scheme is given by the Bode Sensitivity Integral formula, which characterizes a fundamental limitation of causal feedback. Thus, control theory tools can be used to design feedback communication schemes. Single and multi-user gaussian channels are considered here. In all the cases, best known achievable rates are recovered or improved. Prashanth Padmasola and Nicola Elia in their paper [20] studied the performance of spatially-invariant plants interconnected through a static network. Such structures commonly arise in multi-agent

systems and systems described by partial differential equations with constant coefficients. They introduce a new notion of Bode sensitivity integral for such interconnections of systems and comment on a new Waterbed effect in two dimensions, space and time and evaluate examples to show the role of Bode Integral as a fundamental limitation in feedback interconnection of distributed systems. They establish a Nyquist criterion for stable interconnections valid for infinite size networks and propose a modified Bode sensitivity integral, which is equal to a constant function of the degree of instability of a single agent, and represents the integral of the log of the magnitude of the sensitivity over both time and space frequencies as the network grows infinitely large. This leads to a new water-bed effect which is however not isotropic. Bode Sensitivity Integral given by

$$\frac{1}{2\pi} \int_{-\pi}^{\pi} \ln |\det S(\exp^{j\omega})| d\omega.$$

$$= \sum_{i=1}^{N_p} \ln |p_{u_i}|.$$

where p_{u_i} 's are the open-loop poles outside the open-unit disk. Waterbed effect: which basically says that if a stabilizing controller can attenuate disturbances in some frequency range, then it must necessarily amplify at other frequencies. So, the net integral is equal to a constant. However, it must be noted that the push-pop effect is not Isotropic, as one would expect of a real water bed. Notion of Bode sensitivity integral captures the average instability and should be valuable as a limitation benchmark for large networks. Here, Bode integral is independent of the number of units and the gains of the interconnection. Nicola Elia in his paper [21] shows a general equivalence between feedback stabilization through an analog communication channel, and a communication scheme based on feedback which is a generalization of that of Schalkwijk and Kailath. It also shows that the achievable transmission rate of the scheme is given by the Bode sensitivity integral formula, which characterizes a fundamental limitation of causal feedback. Therefore, one can now use many results and design tools from control theory to design feedback communication schemes providing desired communication rates, and to generate lower bounds on the channel feedback capacity. Single-user Gaussian channels with memory and memory-less multi-user broadcast, multiple access, and interference channels are considered here. In all cases, the results obtained either achieve the feedback capacity, and when this is known, recover known best rates, or provide new best achievable rates. The successful stabilization of an unstable linear system over a Gaussian channel corresponds to an actual communication system, which uses feedback and transmits at a rate equal to the sum of the log of the unstable open loop modes. In paper [22] Jialing Liu and Nicola Elia showed integration of Information, Estimation, and Control, and unified fundamental limitations of information, estimation, and control. Over a discrete-time Gaussian channel with memory, a general equivalence

among feedback communication, estimation, and feedback stabilization was established. It is shown that the achievable information rate in the feedback communication problem can be alternatively given by the decay rate of the Cramer-Rao Bound (CRB) in the associated estimation problem, or by the Bode sensitivity integral in the associated control problem. Therefore, it is concluded that the fundamental limitations in information transmission i.e. achievable information rate, in information processing i.e. CRB, and in information utilization i.e. Bode integral, seemingly different and usually separately treated, are in fact three sides of the same entity. Here, the possibility of extending the results to channels in continuous-time and channels not in feedback loops is also briefly discussed. There is a general equivalence among a feedback communication system over a Gaussian channel, an estimation system over the same channel, and a control system over the same channel. Roughly speaking, in steady state, the communication system achieves reliable communication if and only if the estimation system has bounded estimation error and if and only if the control system is stabilized in closed-loop. Hence, the Feedback Communication Limitation is the Achievable Rate; Estimation Limitation is the CRB Decay-Rate (where, CRB-Cramer-Rao Bound) and the Control System Fundamental Limitation is the Bode Sensitivity Integral. It is pertinent to find that **Achievable Rate in Feedback Communication System = 1/2 Decay-rate of CRB in Estimation System = Bode Sensitivity Integral in Control System**. Encoding is essentially a Control Problem and Decoding is essentially an Estimation Problem as stated by Sanjoy Mitter. There exists a critical value for the signaling rate, above which reliable communication is not achievable and below which reliable communication is achievable. In the (recursive) estimation system, the fundamental limitation is the decay rate of Cramer-Rao bounds (CRB): whatever estimator one may design, the decay rate of mean-squared error (MSE) cannot be made faster than the decay rate of CRB. In the control system, the fundamental limitation is the Bode sensitivity integral. No matter how one designs the controller, the sensitivity integral cannot be made smaller than a constant determined by how unstable the plant is. Hence, the fundamental limitations in the three systems agree. That is, the achievable rate in the feedback communication system equals half of the decay rate of CRB in the estimation system, and equals the Bode sensitivity integral in the control system. Kalman filtering leads to the optimal feedback communication! Thus, it is said that the three problems: the optimal estimation problem, the optimal feedback communication problem, and the minimum-energy control problem, are equivalent and hence if any one of the problems is solved, then the other two are solved. In the steady state, the communication system achieves reliable communication if and only if the estimation system achieves bounded estimation error (in terms of second moment) and if and only if the control system is stabilized in closed loop. The optimality in the three systems coincides, based on which the optimal feedback communication scheme can be constructed. The structure of the optimal scheme is given by a simple transform of the Kalman filtering system, and the parameters of the op-

timal scheme are given by the solution to a finite dimensional optimization problem. The presence of Kalman filtering leads to optimal feedback communication. The Kalman filtering for an unstable process driven by its initial condition, when put in an appropriate form, is optimal in information transmission. The one-step prediction operation in Kalman filtering leads to minimization of the channel input power, and the smoothing operation in Kalman filtering leads to optimal recovery of the transmitted message. The perspective of unifying communication, estimation, and control is applicable to various Gaussian channels with feedback, including discrete-time (DT) ISI Gaussian channels (i.e. frequency-selective fading Gaussian channels), DT time-selective Gaussian fading channels, DT ISI dirty-paper coding Gaussian channels and continuous-time (CT) ISI channels. Here, dirty paper refers to the communication problem over a channel with both noise and interference and where the interference is known to the encoder non-causally and unknown to the decoder. This problem is regarded as a basic building block in communication, and it has been extensively investigated by Costa and other researchers. As suggested by Sanjoy Mitter, in feedback communication, the encoding is essentially a control problem, and the decoding is essentially an estimation problem. Hence, the achievable information rate is limited by the performance of the associated control/estimation systems. Additionally, in problems of control/estimation under communication constraints, the control/estimation performance is limited by the available information. Thus, it is natural to expect that the fundamental limitations for information, estimation, and control coincide for various systems with channels in loops. In paper [23] Elia showed multiple systems connected over an unreliable communication network. The links in the networks are modeled as drop-out channels. Here, it is considered that the closed loop Mean Square stability of multi agent systems formations, and the analysis result was used to evaluate the fragility of the networked system to packet losses or link drop-outs. Here, a case is presented where the packet drops can lead to loss of Mean Square stability. Systems that are not Mean Square stable have heavy tail distributions of their states. Simulations show the power law nature of such distributions. While having identical agents may lead to a simplified nominal stability analysis and to scalable solutions, it does not seem to reduce the complexity of the Mean Square stability analysis. It is illustrated that fading networks, which are spatially invariant in the mean, do not suffer from this limitation and allow for the maximal tolerable uncertainty to be distributed arbitrarily among the links. They have demonstrated that networked control system can behave according to power laws if the communication network is fading or unreliable. Based on their previously developed framework, they have shown that there is a critical value above which Mean Square stability is lost determining the slope of the power law. It is argued that the limited communication is a main mechanism for the emergence of the power laws in interconnected systems, and that the result of this paper can be far reaching in the study of complex systems. The paper [24] by Zhang and Hristu discusses

the stabilization of a networked control system (NCS) in which sensors and actuators of a plant exchange information with a remote controller via a shared communication medium. Access to that medium is governed by a pair of periodic communication sequences. Under the model utilized here, the controller and plant handle communication disruptions by ignoring (in a sense to be made precise) sensors and actuators that are not actively communicating. This choice has the effect of significantly reducing the complexity of selecting control/communication policies. It is shown that, for discrete-time NCS, the reachability and observability of the plant can be preserved if the communication sequences are chosen properly. They propose a method for exponentially stabilizing a NCS by first identifying a pair of communication sequences that preserve reachability and observability and then designing an observer-based feedback controller based on those sequences. In paper [25] Guo, Verdu et al. shows a new formula that connects the input-output mutual information and the minimum mean-square error (MMSE) achievable by optimal estimation of the input given the output. That is, the derivative of the mutual information (nats) with respect to the signal-to-noise ratio (SNR) is equal to half the MMSE, regardless of the input statistics.

$$\frac{dI(SNR)}{dSNR} = \frac{1}{2} mmse(SNR).$$

Where, mutual information $I(\mathbf{x}, \mathbf{y})$ between the input \mathbf{x} and the output \mathbf{y} of a channel, and $MMSE$ is the minimum mean-square error in estimating the input with a given output. Regardless of the input distribution, as long as the input-output pair are related through additive Gaussian noise. Signal-to-noise ratio (SNR) of the channel be denoted by SNR . In fact, this relationship and its variations hold under arbitrary input signaling and the broadest settings of Gaussian channels, including discrete-time and continuous-time channels, either in scalar or vector versions. This relationship holds for both scalar and vector signals, as well as for discrete-time and continuous-time non-causal MMSE estimation. This fundamental information-theoretic result has an unexpected consequence in continuous-time nonlinear estimation: for any input signal with finite power, the causal filtering MMSE achieved at SNR is equal to the average value of the non-causal smoothing MMSE achieved with a channel whose SNR is chosen uniformly distributed between 0 and SNR . In a wider context, the mutual information and mean-square error are at the core of information theory and estimation theory, respectively. The input-output mutual information is an indicator of how much coded information can be pumped through a channel reliably given a certain input signaling, whereas the MMSE measures how accurately each individual input sample can be recovered using the channel output. In paper [26] Daniel P. Palomar and Verdu generalizes the link between information theory and estimation theory to arbitrary channels, giving representations of the derivative of mutual information as a function of the conditional marginal input distributions given the outputs. In the paper [27], Nair and Evans formulated a communication-limited control problem for linear

plants with initial output probability density \mathbf{p} . It was shown that the optimal finite horizon coder-controller is an optimal quantizer for the initial condition that has been formulated to operate sequentially. Asymptotic quantization theory was then used to directly obtain the limiting scheme as the horizon approaches infinity. Under certain technical conditions on the initial condition probability density, this scheme is optimal in an infinite horizon sense and yields a necessary and sufficient condition, in terms of the coding alphabet size and dynamical constants, for a given plant to be asymptotically stabilizable in m/h output moment. The emerging area of control with limited data rates incorporates ideas from both control and information theory. The data-rate constraint introduces quantization into the feedback loop and gives the interconnected system a twofold nature, continuous and symbolic. In the paper [28] Nair, Zampieri, Fagnani and Evans reviewed the results available in the literature on data-rate-limited control. For linear systems, it was shown how fundamental trade-offs between the data rate and control goals; such as stability, mean entry times, and asymptotic state norms emerge naturally. While many classical tools from both control and information theory can still be used in this context, it turns out that the deepest results necessitate a novel, integrated view of both disciplines. The improvement from boundedness to asymptotic stability above becomes possible by permitting the quantizer or encoder to possess memory, and follow an adaptive zooming-in / zooming-out strategy. This is based on dynamically adjusting the range of the quantizer so that it increases as the plant state approaches the target (zooming-in phase), and decreases if the state diverges from the target (zooming-out phase). The underlying intuition is that, in order to drive the state to the target, the quantizer resolution should be high, close to the target but coarse far from it. In this paper [29] Nair and Evans discussed the problem of stabilizing a general stochastic linear system in mean square state norm under a feedback data rate constraint was investigated. By employing information theoretic techniques and a new quantizer error bound, an expression was derived for the smallest data rate above which such a system is stabilizable by a coding and control law, without imposing any structural or computational constraints and with very mild conditions on the system noise. This infimum rate is determined only by the unstable eigenvalues of the dynamical matrix and it was demonstrated that as the data rate approaches it from above the mean square states become unbounded for any coder-controller. To establish the attainability of this bound, a finite-dimensional scheme was constructed and shown to achieve stability at data rates arbitrarily close to it. In paper [31] Liberzon et al. considers the problem of achieving input-to-state stability (ISS) with respect to external disturbances for control systems with linear dynamics and quantized state measurements. Quantizers considered in this paper take finitely many values and have an adjustable zoom parameter. Building on an approach applied previously to systems with no disturbances, we develop a control methodology that counteracts an unknown disturbance by switching repeatedly between zooming out and zooming in. Two specific control strategies

that yield ISS are presented. The first one is implemented in continuous time, while the second one incorporates time sampling. We discover that in the presence of disturbances, time-sampling implementation requires an additional modification which has not been considered in previous work. This paper [31] by Hespanha and Liberzon is concerned with the problem of stabilizing a nonlinear continuous-time system by using sampled encoded measurements of the state. They demonstrate that global asymptotic stabilization is possible if a suitable relationship holds between the number of values taken by the encoder, the sampling period, and a system parameter, provided that a feedback law achieving input-to-state stability with respect to measurement errors can be found.

III. CONCLUSION

Several recent results are presented here on issues of control performance under communication constraints based on the survey of the work done by the entire world community. This survey may not give 100 percent exhaustive coverage of all possible papers but the authors have tried their best to cover up the maximum relevant contents without going through the details of Quantization, NCS and some other issues. In fact, Quantization is especially important for networks designed to carry very small packets with little overhead (e.g. applications like CAN based Network, Wireless Networked Embedded Systems, Sensor Network, etc.) because for such networks bandwidth/battery-power etc. can be saved by proper encoding, estimation and sending actuation signals using small number of bits. It is observed repeatedly and emphasized by the scientific and technological communities that there is a growing need of converging control, communication, computation, information and estimation theories though some bold and positive steps are taken by some people. With the rapid growth in mobile / wireless communications, one can easily visualize applications where a large number of mobile units must be controlled over the limited capacity communication channel offered by costly and limited radio spectrum. Due to limited resources of power, speed, bandwidth we must take into account the scheduling, prioritizing, pipelining, buffering like concepts while designing and implementing such systems.

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