

Wireless Sensor Networks for Networked Manufacturing Systems

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1. Trend towards the Networked Manufacturing Systems

With the continuing trend towards globalization and focusing on high value with low volume, the manufacturing system architecture is evolving from traditional centralised model to the distributed model and to the recent networked model. In the modern manufacturing environment, the manufacturing systems are in networked framework via a variety of networking communication systems integrating the heterogeneous collections of manufacturing equipment, devices and real-time information. Such networked manufacturing system monitors and controls with the clear objective of maximizing the Quality of Service (QoS) provided by the prevailing manufacturing resources and to achieve near zero down time operations.

For such networked framework for manufacturing and execution, the key issue is how to sustain networked manufacturing operations' capability in providing robust, zero-breakdown performance with various uncertainties (e.g., machine breakdown, device malfunction, sensor failure, communication delay, and data loss). The challenge therefore lies in the identification, characterization and generalization, and development of technologies to minimize their adverse impact on system performance and serviceability.

Hence from the aspect of system availability, substantial research efforts have devoted to the prognosis of equipment condition. The objective is to prolong the useful life of critical manufacturing elements by estimating the life span of components, devices and equipment. This kind of technology is widely utilized for maintenance operations with the help of the advancement of sensor and sensor fusion techniques. From the perspective of manufacturing control, the machine health information is able to reflect the prevailing health status of the equipment and influence the control decision for networked manufacturing systems. The supervisory controllers are able to take proactive measures to ensure the continual operation by executing the fall back strategies.

However from the aspect of system performance, considering the networked manufacturing systems that are connected through heterogeneous networks, hence, the decision making process is distributed to the individual control agents based on the common global goal. The collaborative decision ensures to make best choice from the consideration for all possible options. Various network models can be applied for such networked manufacturing system, particularly the wireless communication for sensory information fusion. Though such

wireless communication systems provide more flexibility for the system implementation, such infrastructure imposes a lot of other constraints and uncertainties that have a major impact on the system stability and performance. Such important technological challenges appeal to a solid theoretic methodology to properly handle such uncertainties to promise the converged collaborative decision making.

In a nutshell, in networked manufacturing environments, the hybrid model involves both the supervisory controllers and the lower-level controllers. This kind of hybrid model is to be integrated with manufacturing resource management at higher system level and machine health condition at lower equipment level. Hence, it will provide optimized control strategies based on distributed model predictive control (MPC) method for the networked manufacturing systems composed of a myriad of decentralized equipment and sub-systems. The distributed MPC involves the decomposition of the overall control optimization problem into a number of small coupled optimization problems. The allocated resources and their constraints provided by the available resource as well as the health information of the devices will be incorporated in the optimization. In the control design, network uncertainty including data losses, data disorder, random delays, and constraints in bandwidth and sensor node energy will also be considered.

2. Technologies and Standards for Networked Sensing and Control

For networked manufacturing systems, the high value manufacturing activities are more dependent on continuous real-time information from the manufacturing environment for decision making and performance optimization. For such industrial automation applications, considering the increasing requirement for more intelligent distributed control and more demanding needs of condition-based monitoring, the opportunities to apply techniques of networked sensing and control are exploding with decreasing cost of embedded processors, sensors and networking devices for such applications.

The advent of wireless communication and micro-electromechanical systems (MEMS) technologies has provided possibility to bring embedded controller, sensors and wireless communication module together as one integrated component for networked sensing and control systems, enabling remote sensing and actuation over wireless channels. Such sensors and actuators based on standard wireless interface and protocols provide new paradigm for factory automation as they converge the sensing, control, computation and communication capabilities into a single tiny node.

Hence, wireless sensor network (WSN), based on the above concept, has been proven to be one of the best platforms for networked sensing and control systems for the factory automation applications in the networked manufacturing systems. WSN is a mesh network consisting of small sensor nodes that acted as the smart layer between virtual and physical world. Integrated with capabilities of communication, computation and various sensing, each node can be imaged as an intelligent tiny device (Fig. 1) with battery energy support for distributed monitoring, estimation and control applications. With wireless communication capability, data captured by individual nodes of WSN from the observed phenomenon can be processed locally or autonomously delivered to a gateway for distributed collaborative information processing and decision making.

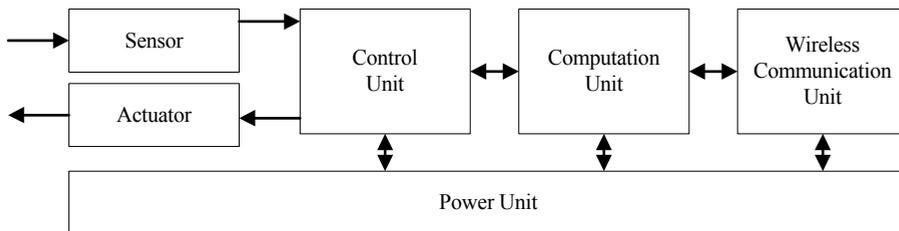


Fig. 1. Functional Blocks of Wireless Sensor Network (WSN) Node

Hence, WSN provides new paradigm for real-time control applications for military, industry and environment monitoring purpose. Applying various sensors for different industrial control and monitoring applications that are supported by the IEEE 802.15.4 communication standard, WSN has demonstrated great potentials for networked sensing and control systems. Fig. 2 shows the major categories of sensors for WSN applications and their market growth trend in future industrial automation. Many products have been available in recent years (Fig.3).

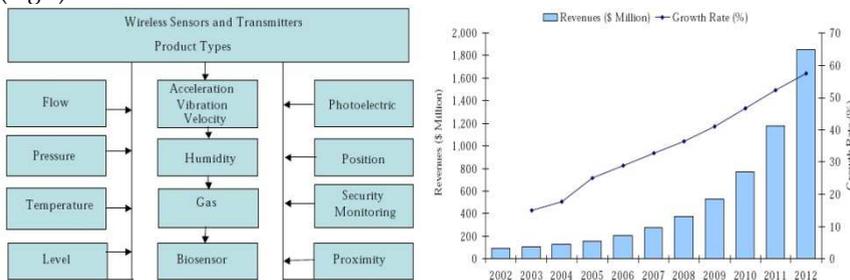


Fig. 2. Wireless Sensors and Market Trends (Source: Frost & Sullivan)



Fig. 3. MicaZ: WSN product (www.xbow.com)

The wireless communication and services have greatly enabled e-manufacturing providing more information efficiency for industrial applications at enterprise level. However, at the shop floor level, the fundamental networking technology for control information is still based on fieldbus (IEC 61158 standard) providing wired link between program logical controllers (PLC) and other physical devices such as transducers, actuators, motors and switches to form the control chain. Although, in recent years, the radio-frequency identification (RFID) technology provided electronic identification labels for object identification and asset tracking in the factory yet lacks support for sensing, information processing and actuation by its transponders. To simplify the machinery control and

monitoring in harsh environments and to reduce the cost of cable installation and maintenance by using mobile device, wireless personal area network (WPAN) based on IEEE 802.15 standards become new foundation technologies in factory automations. Standardization of WSN is one of the most important industrial drives to its commercial success for factory automation application. The standardization processes are focus in two areas: network protocol and sensor interface. The prior is described in the latest ZigBee specification which is defined on top of IEEE 802.15.4. The later is also referred as transducer electronic data sheet containing interface information connected to any kinds of sensors and this standard is defined in the IEEE 1451. The standardization helps to reduce the cost of the system deployment and shorten the cycle of development.

2.1 IEEE 802.15.4 and ZigBee

IEEE 802.15 Wireless Personal Area Network (WPAN) defines standards for short distance wireless networks including following five sub-standards: IEEE 802.15.1 for Bluetooth used for short range devices, IEEE 802.15.2 for coexistence, IEEE 802.15.3/3a for high data throughput with low power consumption in short distance which is also known as ultra wideband (UWB), IEEE 802.15.4/4a for low rate WPAN and IEEE 802.15.5 for mesh network. Especially, the IEEE 802.15.4 defines a standard for a low data rate solution with long battery life and very low complexity which can be used in factory control and monitoring. It is intended to operate in an unlicensed, 16 channels in the 2.4GHz industrial, scientific and medical radio band or 10 channels in the 915MHz or one channel in the 868MHz band (Fig. 4).

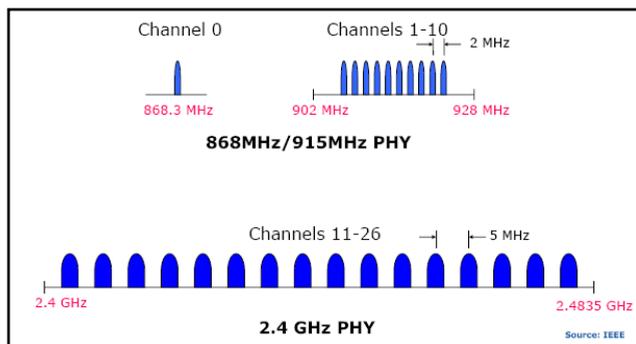


Fig. 4. IEEE 802.15.4 Channel Allocation (source: IEEE)

With the completion of standardization of the Media Access Control (MAC) Layer and Physical (PHY) Layer of 802.15.4, the industrial focus has been shifted to upper protocol layers and application profiles. The ZigBee Alliance is a group of companies which maintain and publish the ZigBee standard. ZigBee is the standard designed to address the unique needs of most real-time control and monitoring application in the factory automation. ZigBee has developed upper layers of the stack and application profile, which is shown in Fig.5. The ZigBee Alliance (www.zigbee.org) has been setup to enable reliable, cost-effective, low-power, wirelessly networked monitoring and control products based on IEEE 802.15.4. The specification defines three throughput levels: 250 Kb/s at 2.4 GHz, using 10

channels; 40 Kb/s at 915-MHz, using 6 channels; and 20 Kb/s at 868 MHz using a single channel.

Application Framework	ZigBee Device Object (ZDO)
Application Support Sub-layer (APS)	
Networking Layer (NWK)	
Data Link Layer	
IEEE 802.15.4 LLC	IEEE 802.2 LLC Type 1
IEEE 802.15.4 MAC	
IEEE 802.15.4 PHY (868/915 MHz)	IEEE 802.15.4 PHY (2400 MHz)

Fig. 5. IEEE 802.15.4 and ZigBee Stacks

2.2 IEEE 1451

As transducer is key part in the WSN used for industrial control and process monitoring, coherent open standard for sensor interface provides foundation for market adoption and successes. The standard provides seamless integration, interoperability and scalability for larger WSN to be deployed in the shop floor and coexist with existing wired control and monitoring systems.

IEEE 1451 is the family of standards for a networked smart transducer interface which provides the common interface and enabling technology for the connectivity of transducers to control devices, data acquisition systems and fieldbus. The key definition of data formats and communication protocols of Transducer Electronic Data Sheet (TEDS) have been specified in IEEE 1451.2 (1997). IEEE 1451.1 (1999) developed a smart transducer object model in frame of network-capable application processors (NCAPs) to support multiple control networks. IEEE 1451.3 (2003) extends the parallel point-to-point configuration to distributed multidrop systems. IEEE 1451.4 (2004) is an emerging standard for adding plug and play capabilities to analog transducers via a mixed-mode interface of analog and digital operating modes. IEEE 1451.5 (2007) defined the wireless communication and TEDS formats and specified sensor-to-NCAP connection for IEEE 802.11 family, IEEE 802.15 family or Ultra-wideband (UWB) connections. IEEE 1451.6 (Draft) proposed the TEDS using the high-speed CANopen network interface for measuring devices and closed-loop controllers. Fig. 6 shows the general framework of smart transducer interface of IEEE 1451 family.

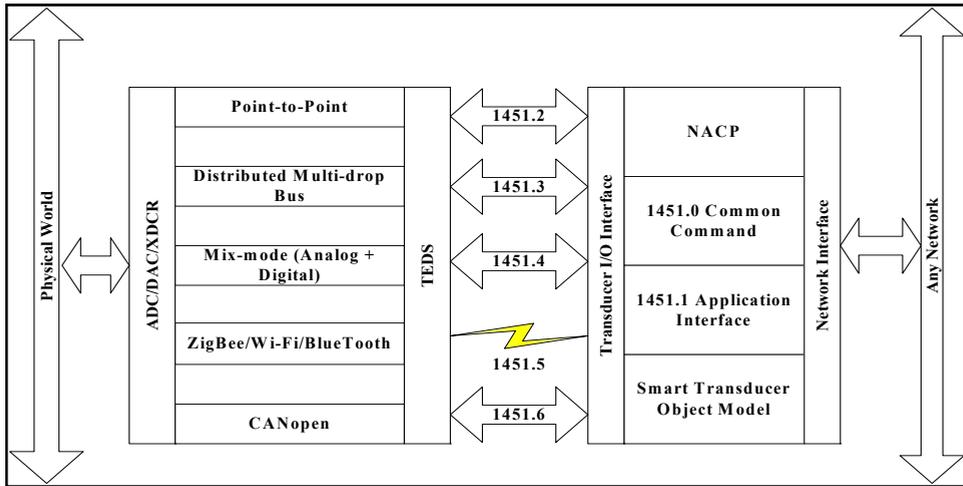


Fig. 6. IEEE 1451 Family (source: IEEE)

2.3 Standard Architecture for Condition-based Maintenance Application

As factory automation is moving towards more advanced, sophisticated and expensive machinery and devices, it calls for information exchange standard and architecture for the diagnostics and maintenance at application level. Intelligent condition-based maintenance (CBM), a maintenance philosophy for machinery and equipment, is a form of proactive maintenance that make use of sensors, sensor networks and computational intelligence techniques to efficiently forecast incipient failures and predict the remaining useful life of the equipment, based on real-time assessment of equipment condition, to perform maintenance only when there is objective evidence of need, so as to ensure near-zero downtime, and to minimize the total cost of maintenance.

Open System Architecture (OSA) for CBM has been developed and promoted by the team participants from the university, standard consortium, industry and military organization to demonstrate the system architecture that facilitates interoperability of CBM software modules. As the results, the seven functional layers are defined within the OSA-CBM development process: Data Acquisition, Data Manipulation, Condition Monitor, Health Assessment, Prognostics and a Human Interface or Presentation layer. Each layer has the capability of requesting data from any functional layer as needed and data flow will occur between adjacent functional layers.

The open architecture has finally evolved into a set of standard guidelines including ISO 13374 for Condition Monitoring and Diagnostics of Machines with four parts: General Guidelines, Data Processing, Communication and Presentation; Machinery Information Management Open Systems Alliance (MIMOSA) Open System Architecture for CBM as well as for Enterprise Application Integration (2006). Many applications have been developed under this guideline in recent years (Djurdjanovic et al., 2003; Chidambaram et al., 2005; Park et al., 2006).

3. Research Issues and Challenges

The new element in the networked control and sensing is the network communication. With each component making its own control decision locally based on own or neighbouring sensory data, they can coordinate each other and be able to achieve global targets of many industrial control and monitoring applications. The network architecture allows sensors, and other control agents such as actuators and controllers to be interconnected together, using less wiring, and requiring less maintenance than the point-to-point architecture. Such architecture also makes it possible to distribute processing functions and computational traditional loadings into several small units. Moreover, distributing control between multiple processors can make the system more flexible and fault-tolerant whereas centralized control suffers from the drawback of a single point of failure. Such networked sensing and control systems which built on sparse and unreliable networked components posed new research challenges from two aspects: control over networks and control of networks (Murray et al., 2003).

3.1 Control over Networks

For the control over packet-based communication channels, several key issues have been addressed making networked sensing and control systems distinct from other control systems in the face of bandwidth constraints, channel fading and competition for network resources (Nair et al., 2007)

As many networked sensing and control systems are based on wireless networks, control performance tends to degrade when wireless communication channels show the characteristics of packet loss, packet delay and packet disorder; therefore communication reliability has great impacts on system stability (Nair et al., 2007). The relationship between the stability of the system and data rate of communication was explored at both Transmission Control Protocol (TCP) level and User Datagram Protocol (UDP) level (Schenato et al., 2007). The relationship between the stability of the system and data distortion was also explored to show the unstable error region by analyzing the statistical convergence properties of the error covariance matrix of sensor measurement (Liu & Goldsmith, 2004) and some results also revealed the upper bound of the expected error covariance for convergence (Elia & Mitter, 2001) as well as the critical value for the arrival rate of observations for bounded state error covariance (Sinopoli et al., 2004).

Researchers now pay more attention on efficient quantizer design for obtaining stability for such data-rate limited control system and have showed that the coarsest quantizer for quadratic Lyapunov function is logarithmic (Ishii & Francis, 2002). More significant results were reported applying sector bound approach for performance analysis of logarithmically quantization systems (Fu & Xie, 2005).

3.2 Control of Networks

For the control of networks, some basic problems have been widely explored in the research community including network congestion control, network routing strategies, transmission power management and application level performance analysis based on quality of service (QoS). These efforts have brought network protocol design into modular-based layered architecture that has evolved into seven-layer Open Systems Interconnection (OSI) model including physical, data link, network, transport, session, presentation, and application.

Due to the characteristics of nodes uncertainty, variation and limited resources such as communication channels, network bandwidth and power supply, the dynamic characteristic features of WSN infrastructure require research work for the design and development of network protocols, topology, routing, data dissemination, power scheduling, programming methods and data abstraction. These issues lead to the efforts and results for standards of WSN infrastructure that are important drives to commercial success of WSN especially for factory automation applications. These standards include IEEE 802.15.4, Zigbee and IEEE 1451.

3.3 Control and Communication Co-design

Facing the challenges from both control demand and communication provision, there is a need to take a holistic approach to both aspects for building reliable application while considering the unreliable infrastructure for the above scenarios. Hence deciding the right architecture for the convergence of communication, control, and computing becomes one of the research challenges when applying holistic view for both communication performance and control performance (Murray et al., 2003). Since classical communication theory and control theory have not shown a ready unified mathematical model for these new research challenges, there is a need to develop new approaches and techniques for optimization problems in networked sensing and control systems.

As WSN is a data-driven computation platform for factory monitoring, process control and supervisory control, optimization is needed for both control and communication performance. Such trade-off requires new design methods for the traditional layered OSI model with consideration of sensing and control objectives (Goldsmith, 2005). It requires the cross-layer consideration rather than layer by layer modulation for system optimization involving different factors from multiple layers. The cross-layer consideration is driven by requirement at application level due to the nature of WSN-based applications.

4. Optimization Techniques for WSN in Networked Sensing and Control

With emerging technology of WSN as low power pervasive computation platform for monitoring and distributed control, research on WSN in area of cross-layer design becomes more important. Comparing with the OSI-based model which is more connection oriented, with less constraints and for more general purposes of usage, WSN is task oriented, with more constraints, more data-driven features and application specific requirements. Hence, research work on WSN in area of cross-layer design becomes more important due to these unique characteristics such as distributed network management, distributed decision and energy-constraints for the individual nodes. The tradeoffs between network lifetime, node connectivity, data accuracy and network throughput require richer interactions among the physical, networking and application layers (Fig. 7). The motivating drives for cross-layer design fall into two categories: from infrastructure aspect such as prolonging the network lifetime (Hoesel et al., 2004) and from application aspect such as providing reliable data fusion for control and estimation requirement (Xiao et al., 2006).

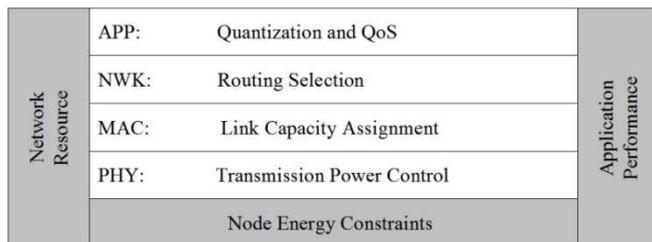


Fig. 7. Cross-layer Optimization Model

There are two directions of the research work to consider and apply cross-layer design and optimization for the sensing and control applications using WSN:

- Cross-layer design from aspect of network utility and performance optimization
- Cross-layer design from aspect of sensing and control performance

4.1 Cross-layer Design for WSN from Network Infrastructure Aspect

From infrastructure aspect, there are several issues to be considered for cross-layer design:

- Power constraints: as WSN node relies on battery power, it requires efficient power management to maximize the lifetime of the node as well as the system. Power consumption is not only related with the physical layer (PHY). It is also decided by a set of variables at different layers such as media access control (MAC) layer and networking (NWK) layer. Hence power consumption management requires joint optimization of factors across PHY, MAC and NWK layers.
- Network properties: due to the possible channel error, the node application is vulnerable to packet loss and disorder. The mobility nature brings more issues to the interference at PHY layer, access scheduling at MAC layer and network routing at NWK layer. Maximization of the network utility should be resolved by the coordination for PHY, MAC and NWK layers.

Most of the studies from infrastructure aspect have shown the benefits by joint design across NWK, MAC and PHY layers without considering QoS at application level. For example, based on the single layer energy optimization strategies for MQAM and MFSK modulation, Cui et al. demonstrated modulation optimization at physical layer with energy model considering two power status: active and sleep (Cui et al., 2003); then they extended the approach by introducing a variable-length interference-free TDMA scheme to minimize the total energy consumption by joint consideration of MAC and PHY layers that was solved by convex relaxation methods (Cui et al., 2004); and they further extended joint optimization model to the routing layer and showed results that optimization solution should go for multi-hop routing when only transmission energy was considered, but need to go for single-hop transmissions if circuit processing energy was considered as well (Cui et al., 2005). Cui summarized the above results on the cross-layer optimization in WSN with energy constraints by modulation, physical transmission and network communication routing and showed the benefits by joint design across routing, MAC, and PHY layers in his PhD dissertation.

Madan et al. proposed a cross-layer optimization model for minimizing the maximum energy consumption of any node in the network for the purpose of maximizing the network lifetime. This approach considers load balancing factor in the multi-hop model, channel

utilization based on TDMA schema as well as transmission power and transmission rate. As this non-linear problem of multi-layer optimization problem for lifetime maximization model is NP-hard, it was simplified into mixed integer convex optimization problem by convex relax using interference-free TDMA assumption (Madan et al., 2005). Their work showed a distributed algorithm which starting with a feasible suboptimal solution and finally converging to optimal solution through limited iterations.

Cross-layer approach has also been tried out in the TinyOS which is de-factor standard and open source embedded operating system for many sensor network platforms. An adaptive cross-layer framework called TinyCube provides a generic interface and a repository for the multi-layer information exchange and management (Marron et al., 2004). Under the IEEE standard 802.15.4, cross-layer between MAC and PHY has been explored using a distributed algorithm to manage the activities of sensor nodes (Misic et al., 2006).

4.2 Cross-layer Design for WSN from Application Requirement Aspect

When feedback loop of a control system is built on wireless communication channels, the communication performance has major impacts on the performance of control systems. However QoS requirements in application layer play a leading role for cross-layer optimization modelling, hence more and more work from application aspect showed the importance that cross-layer optimization should be driven by the consideration of application layer for WSN application.

Mostofi et al. analyzed tradeoffs between communication and objective tracking target, and developed algorithms to handle the optimization problem with interference between physical energy consumption and tracking accuracy of application layer for the real-time tracking applications; and they also proposed the cross-layer strategy of sharing information between the PHY layer and application layer in the design of Kalman filter for the real-time estimation based best linear unbiased estimator (BLUE) for the location estimation which demonstrated the estimation benefits and infrastructure cost saving (Mostofi et al., 2005).

Liu et al. studied the tradeoffs of data rate, time delay and packet loss in the communication link layer design. They proposed an analog soft-decoding wireless link design for robust distributed control systems (Liu & Goldsmith, 2005).

Cooperative estimation using WSN with energy-efficient method is another important research area of cross-layer optimization. Xiao et al proposed a joint optimization approach using BLUE to minimize the noise distortion while consuming minimum power of sensor nodes. In a scale signal joint estimation case, the approach tried to minimize the total transmitting power by the optimal sensor scheduling to turn off the node with higher mean square error (MSE) or lower the quantization level however still keeping overall MSE under threshold (Xiao et al., 2004). Xiao extended his work to the joint estimation problem for vector signal case, and use MSE as performance measurement as well (Xiao et al., 2008). In this case, they proposed an optimal linear decentralized estimation model with coherent media access control and resolved the problem analytically for the case of noiseless MAC and solved the noisy MAC problem using semi-definite programming (SDP). However their models only support the star networking architecture where there is only one hop from end node to fusion centre. Real-time object tracking and position estimation were widely used test bed for demonstration of applying Kalman filter on WSN. Sun et al used Kalman filter for target states estimation for the linear model with multiple packet dropouts (Sun et al. 2008).

However the above work only provided piecemeal analysis and solutions for specific cases which are focused either on control aspect or on communication aspect and the holistic view of whole stack is not presented. In the face of complex interactions required by the cross-layer approach, there is a need to build a general model to address the cross-layer issue with network utility maximization and different targets at application layer. Hence the more formal and common mathematical language is required to provide fundamental optimization modelling and techniques for cross-layer design. Such mathematical theory of network architecture is called “Layering as Optimization Decomposition” which is defined as top-down approach to design protocol stacks (Chiang et al., 2007).

4.3 Mathematics Framework Cross-layer Design and Optimization

Cross-layer optimization requires more quantitative analysis using a common language and unified mathematical framework. Mathematical decomposition techniques have emerged as a foundation for communication network maximization problems in recent years and myriad work was inspired by Kelly’s model (Kelly et al., 1998). Kelly’s model of optimization decomposition framework provides a common language for top-down design based on coordinating sub-problems from PHY, MAC and NWK layers. The general model is shown in Fig. 8 which considers the optimization targets at application layer as well. The model also shows general optimization targets from point of individual layer.

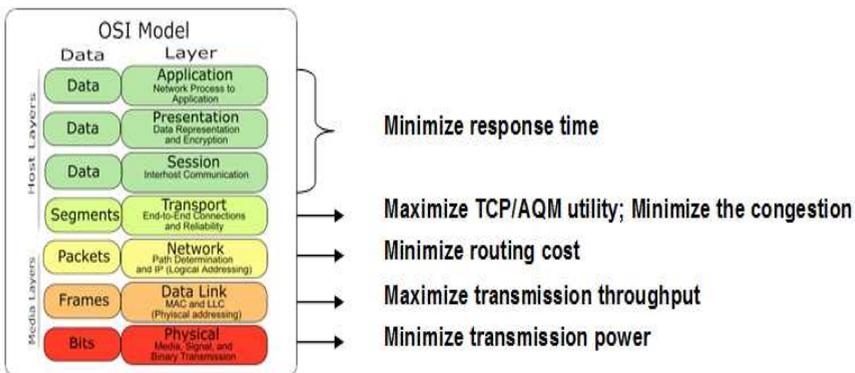


Fig. 8. Cross-layer Optimization Model

The theory proposed by Kelly used a network utility maximization (NUM) as framework to address the cross-layer issues (Kelly et al., 1998). Consider a system for TCP congestion control with routing matrix R , link capacity c , source rate vector x and x_s is source rate for source s , the utility function U_s is given in (1).

$$\begin{aligned} & \max \sum_s U_s(x_s) \\ & \text{s.t. } Rx \leq c \end{aligned} \tag{1}$$

Such model defines NUM problem and provides solution through decomposition techniques by dividing the large optimization problem into smaller sub-problems or by

exploring the space of alternative decompositions called duality when necessary. The NUM defines the objective functions and various constraints at different layers. NUM uses primal or dual variables to indicate what need to do and uses constants values to indicate what resource can be used. It normally applies Lagrange duality theory to find optimal solution. When a NUM formulation is given, decomposition theory is applied rather than centralized computation instead. The optimization decomposition methods can be divided into two categories (Chiang et al., 2007):

- horizontal decomposition method and
- vertical decomposition method

Horizontal decomposition method addresses issues in one layer such as TCP congestion, IP routing and MAC control through the theory of decomposition for non-linear optimization. Vertical decomposition addresses the multi-layer optimization issues. Some existing work can be categorized into following topics (Chiang et al., 2007):

- Joint optimization of congestion control and routing
- Joint optimization of congestion control and resource allocation
- Joint optimization of congestion control and contention control
- Joint optimization of congestion control, routing and scheduling

Decomposition techniques have provided a common language for network optimization problems. These problems can be resolved by primal-dual method, interior method, quadratic programming and geometric programming method etc.

The basic principle of decomposition is to make original complex problem into independent smaller sub-problems in order to be resolved in a distributed way. Most widely used methods are classified into primal and dual decomposition that can be developed into specific distributed algorithm to resolve. More detailed techniques were discussed on optimization decomposition such as decoupling constraints, decoupling objective function and other alternative decomposition including partial decomposition, multi-level decomposition (Chiang et al., 2007).

Despite the progress of the decomposition of a generalized NUM that has been widely reported over the past few years, there are still many open research issues to be resolved such as the rate of convergence; stochastic issues at channel layer, packet level and session level; non-convexity issues etc. To draw the conclusion, cross-layer optimization and related decomposition techniques provide a top-down approach to design network protocol and allocate resource for performance optimization target. Yet few research works have involved object functions for application level targets. Hence control application with control performance and communication networks with resource constraints and optimization provides a common field for new research initiatives. The next section will show some basic ideas and basic system modelling for the control and monitoring applications in networked manufacturing systems. It shows new approaches which are different from the existing methods. The basic system modelling, simulation work, trial industrial prototype will be presented in the following section. The advantages and limitations of the current research approaches and proposal for the future work will be discussed in last section.

5. Industrial Application Case Study

Two industrial application areas are chosen as examples for system design and optimization of sensing and control using WSN. One area is manufacturing asset tracking and

management using WSN to overcome the constraints of RFID technologies which is mainly suitable for pure identification applications. Compared with RFID, WSN is able to track the objects in real-time over large areas without any additional infrastructure required. Another focus area is intelligent condition-based maintenance, a maintenance philosophy for machinery and equipment, which is a form of proactive maintenance that make use of sensors, sensor networks and computational intelligence techniques to efficiently forecast incipient failures and predicts the remaining useful life of the equipment.

5.1 Application 1: Asset Tracking in the Networked Manufacturing Systems

Though UWB or RFID is also widely applied to asset tracking application, but both technologies require power supply for their readers. For the case of some specific requirements such as monitoring the activities of maintenance workers in the cabin of aircraft in airport hangar (Fig. 9), as there is no power supply available for any maintenance activities on aircraft, hence in this situation, WSN is the best choice as both UWB and RFID readers require power supply.



Fig.9. Aircraft Hanger and Cabin

5.1.1 Network Modeling

The model consists of a global fusion centre (coordinator) for estimation, local fusion nodes or network relay nodes (routers) for data dissemination and routing and end nodes (end devices) linking with sensors for getting observation of physical parameters (Fig. 10). This architecture considers generic networking topology which includes both cluster topology and mesh topology for different application requirements with random distribution of sensor nodes.

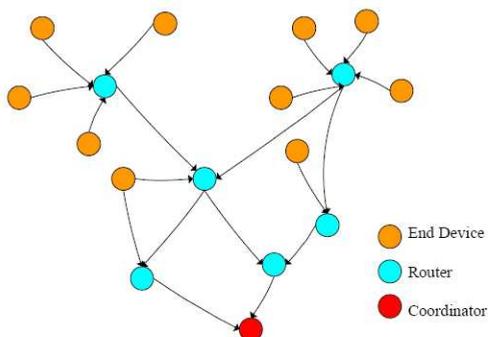


Fig.10 Topology for Networked Sensing and Control

When network routing is considered for WSN with N sensor nodes and L links between nodes, the routing matrix R is defined by an $L \times N$ matrix shown in (2).

$$R_{lk} = \begin{cases} 1, & \text{if link } l \text{ is in any path of source node } k; \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

where $l \in [1, L]$ and $k \in [1, N]$

5.1.2 System Modeling

In the above application framework, we consider the system with N end devices making joint measurement for unknown signals x such as location. The system dynamic model is defined in (3) with zero mean Gaussian noise $\xi[k]$ at discrete time k and A is dynamic characteristics matrix for the system.

$$x[k+1] = Ax[k] + \xi[k] \quad (3)$$

Let the observation from node i ($i=1,2,\dots,N$) be y_i where observation noise v_i is a Gaussian noise with zero mean and observation error covariance matrix is σ_i^2 for each node i . Suppose h is observation characterization matrix, where $h = (\sqrt{g_1}, \sqrt{g_2}, \dots, \sqrt{g_n})^T$ and g_i is the channel power gain for the i^{th} node transmission. The system observation model is defined in (4).

$$y_i = hx + v_i \quad (4)$$

If wireless communication is considered between any two nodes, the channel noise is Gaussian noise with zero mean with error covariance ω_i^2 . Hence the joint estimation given by best linear unbiased estimator (BLUE) for x is given by (5).

$$\hat{x} = \left(\sum_{i=1}^N \frac{g_i}{\sigma_i^2 g_i + \omega_i^2} \right)^{-1} \sum_{i=1}^N \frac{\sqrt{g_i} y_i}{\sigma_i^2 g_i + \omega_i^2} \quad (5)$$

The mean square error (MSE) for the joint estimation is given by (6).

$$\text{var}(\hat{x}) = \left(\sum_{i=1}^N \frac{g_i}{\sigma_i^2 g_i + \omega_i^2} \right)^{-1} \quad (6)$$

When network congestion control is taken into consideration, we define link capacity vector $c = [c_1, \dots, c_L]^T$ for all L links and source rate vector $s = [s_1, \dots, s_N]^T$ for all N nodes. The following relationship (7) should be satisfied.

$$Rs \leq c \quad (7)$$

Link capacity is function of the signal-to-noise ratio (SNR) denoted as (8).

$$c_l = \log(1 + \varphi_l) \quad (8)$$

$$\text{where } \varphi_l = \frac{g_{l,l} p_l}{\sum_{l \neq k} g_{l,k} p_l + \omega_l^2}$$

The source rate shall also maintain the threshold ($\|s\| \geq S_0$) in order to keep certain quantization level and reduce the distortion while power usage should be kept to certain limitation ($\|p\| \leq P_0$) to maintain the network lifetime.

5.1.3 System Optimization

In our application framework, we try to minimize MSE error to increase estimation accuracy while keep power consumption under certain level with consideration of TCP congestion control by rate and link capacity constraints. The MSE error is a function of p if observation variance σ_i^2 is constant. The objective is to minimize the MSE $D(p)$:

$$\begin{aligned} \min \quad & D(p) \\ \text{subject to} \quad & Rs \leq c(p) \\ & \|s\| \geq S_0 \\ & \|p\| \leq P_0 \\ & s \geq 0 \\ & p \geq 0 \end{aligned} \quad (9)$$

The above optimization problem can be resolved by decomposition techniques in principle. By introducing the Lagrange multipliers (λ_0 , λ_1 and λ_2), the Lagrangian can be expressed as follows:

$$L(p, s, \lambda_0, \lambda_1, \lambda_2) = D(p) + \lambda_0 (Rs - c(p)) + \lambda_1 (S_0 - \|s\|) + \lambda_2 (\|p\| - P_0) \quad (10)$$

So the problem can be decoupled into following two sub-problems for $\forall \lambda_0$, $\forall \lambda_1$ and $\forall \lambda_2$:

$$\begin{aligned} \min \quad & \lambda_0 Rs + \lambda_1 S_0 - \lambda_1 \|s\| \\ \text{subject to} \quad & s \geq 0 \end{aligned} \quad (11)$$

and

$$\begin{aligned} \min \quad & D(p) - \lambda_0 c(p) + \lambda_2 \|p\| - \lambda_2 P_0 \\ \text{subject to} \quad & c(p) = \log(1 + \varphi) \end{aligned} \quad (12)$$

Problem (11) is source rate control problem and (12) is power control optimization problem. Problem (11) and (12) can be resolved in application layer and network layer respectively. λ_0 , λ_1 and λ_2 are interface parameters for the cross-layer optimization.

5.1.4 Hardware and Tools

For the test bed for demonstration, JN3159 wireless micro-controller (www.jennic.com), which consists of a 16MHz 32-bit RISC CPU, 96kB RAM, 4-input 12-bit ADC, 11-bit DACs and UARTs for external sensors², is applied for implementation. ISM free wireless communication channels on 2.4GHz are utilized, supporting both IEEE 802.15.4 and ZigBee standards with three kinds of antennas, i.e. on board ceramic, SubMiniature version A (SMA) connector and high power uFl connector for different transmission power range requirements. On such platform, link quality indication (LQI) concept defined in ZigBee standard is taken as signal strength between a pair of transmitter and receiver nodes to estimate the distance.

The initial tests focus on power saving by using less transmission power however still achieving reliable estimation results for fusion center. The experiment results for relationship between distance and LQI values using JN5139 were shown in Fig. 11. For short distance, the distance is defined as $d = (256 / LQI)^\alpha$ and $\alpha = 2$ in this case.

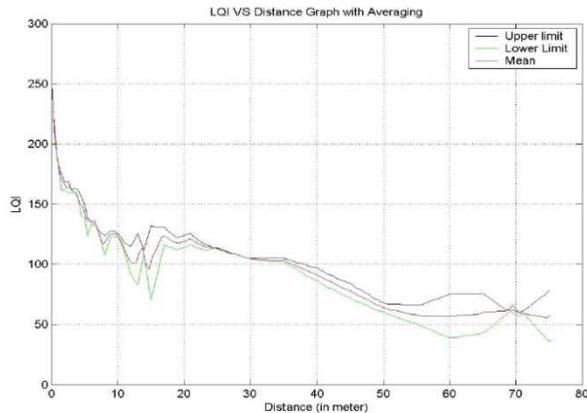


Fig. 11. LQI and Distance relationship

The system design and optimization considers the following factors:

- Transmission power of individual node
- MSE error of LQI value
- Sampling rate

5.1.5 Results

In order to improve the estimation accuracy, we design a fusion algorithm to handle multiple local estimations from a group of sensors. From the estimations of multiple nodes, we discard the LQI readings with higher MSE following the calculation formula in last section, the precision of the location estimation using a few groups of sensor nodes is improved and preliminary results are shown in the demonstration for real time object location. In Fig. 12, we demonstrate the application prototype in the lab environment and show the results on the LCD panel of coordinator node by a block indication. The working principle of estimation process is shown in Fig. 13.

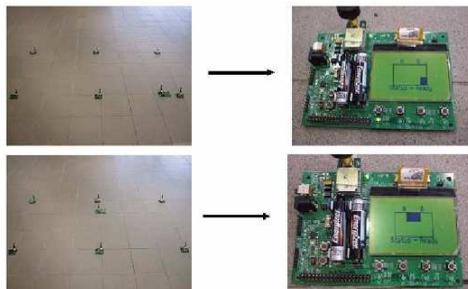


Fig. 12. Test-bed and Demonstration

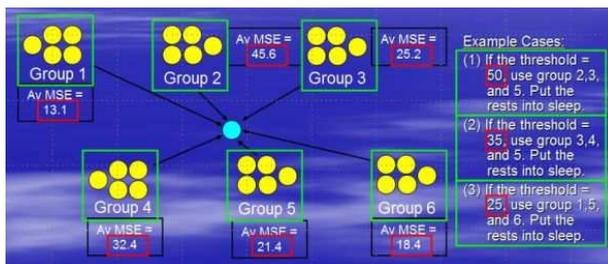


Fig. 13. Optimized Estimation Process

5.1.6 Limitations

Although we build optimization model and improve the estimation accuracy using multiple sensor fusion approach, we still encounter the scalability and mobility issues for such application. While ZigBee provides low power and standard wireless communication protocol, it still has several limitations due to the constraints of Jennic Zigbee stack implementation.

- Constraints for free broadcasting
- Limited memory segment for address recording
- Address-reading first
- Jennic Zigbee stacks default way of networking

The above limitations prevent some ad-hoc application scenarios where nodes with high mobility. It also poses challenges for application implementation for multiple target objects tracking. We are developing new mechanism in the next stage of the project.

5.2 Application 2: Condition Monitoring in the Networked Manufacturing Systems

In this scenario, the Jennic JN5139 wireless sensor evaluation board is used, which contains an analogue to digital peripheral, and can handle the data collection, data processing and transmission functions together. Incorporated with it, a small size, low power, 3-Axis ±3g, frequency bandwidth 1600Hz, iMEMS accelerometer (ADXL330) is connected to the Jennic wireless transmission module through analogue inputs. It draws power from Jennic node and need neither extra conditioning circuit nor amplifier device.

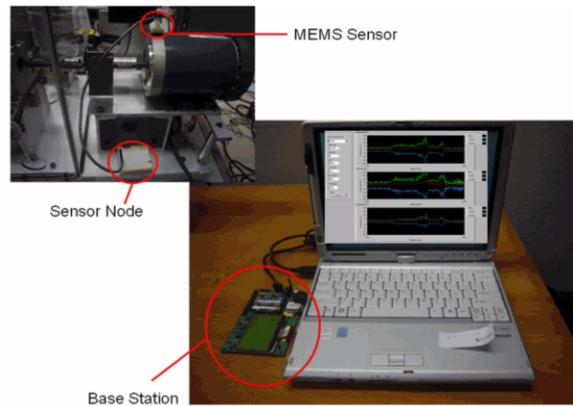


Fig. 14. Wireless Sensor for Machine Condition Monitoring

The system setup is much simpler with lower cost than conventional vibration data collection system. The system also includes the server station to display and store the data and the base-station to bridge the wireless sensor to the server. The system setup is shown in Figure 14.

5.2.1 Maximum Data Acquisition Rate

The maximum data collection rate is confined by

- Sensor node sampling rate;
- Wireless transmission rate; and
- Data transmission from base station to server PC.

Jennic on-board system timer is up to 16MHz. The ADC conversion speed could be configured through the setting of ADC clock division (250K-2MHz) and sampling holding period (2-8 clock periods). The maximum sampling rate could be 10 μ s. So for one channel ADC, the maximum sampling rate is about 100KHz. Consider the sensor node programming cycle time, the actual sampling rate would be less than 100KHz. For 3-axis acceleration data sampling rate should not be higher than 30KHz.

Normally, the larger proportion of user data in the package will get better transmission efficiency. In the case of Jennic SDK, the package size is up to 128 bytes, the header data size is 44 bytes, and maximum data in the package is 84 bytes, or less than 66% of wireless transmission is used for actual testing data transfer. To reduce the rate of payload in the transmission, the combination of data set is the strategy to make good use of every package. Another factor of wireless transmission is the topology of the system. If one node responsible on the data forwarding for other neighbor nodes, the maximum transmission rate for each node will be lower. In mesh network the case would be completed and the networking packages would also share the transmission bandwidth. For the application which request high speed data collection, star topology, and dedicate time slot for each end node is recommended.

If this required data rate is less than the baud rate of the serial communication between the

base-station and server PC, then data could be streaming to the server. When RS232 is configured at baud rate 115200bps, only about 11K bytes could be transferred in one second. The number of data sets to be transferred to server PC also depends on the data format and resolution. 2000 sets of 5 digits data could be received in continuously transfer from RS232 serial port. Our test result also shows that only less than 2% data lost for the 2000 sets/second continuously data collection and transmission to server.

5.2.2 Time Domain Signal Processing

In this test, the machine running speed is less than 3600 RPM, we set the sampling rate 5000/s for the 3 axis acceleration, statistical window size 2000.

The time domain analysis is the majority approach of the vibration signal analysis and especially suitable for on-line condition monitoring using wireless accelerometers. In order to obtain the machine performance from vibration signal in the time domain, following statistical analysis methods have been implemented on sensor node:

- Root mean square
- Peak Value
- Crest Factor
- Kurtosis
- Skewness

5.2.3 Test Cases:

High speed data acquisition is required in machine condition monitoring. With the understanding of the WSNs DAQ limitation and the nature of machine performance, different strategy could be applied for high speed DAQ. Applying above research results, following test cases were created successfully for machine condition monitoring:

Case 1: Motor Current Waveform Monitoring

The induction motor speed limit is 2850 RPM, so the current supply frequency from inverter would not be higher than 50Hz. 1KHz sampling rate is enough for current monitoring - both time domain and frequency domain. Streaming data collection is applied and reliable waveform was collected. The received data is projected in Fig. 15.

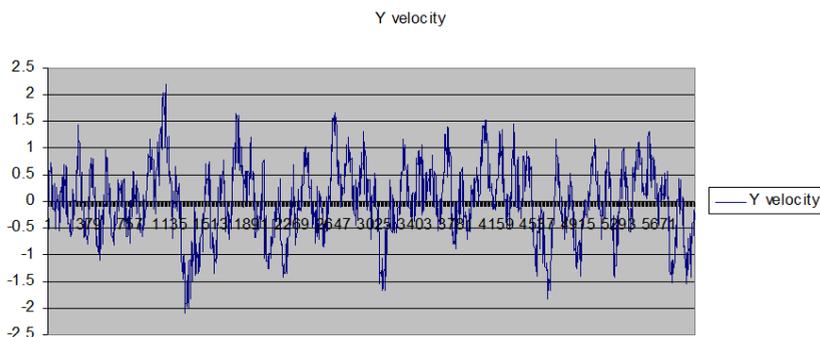


Fig. 15. Current Waveform using WSN

Case 2: Pump Vibration Monitoring

Vibration analysis is a powerful tool for the condition monitoring of rotating machinery. This especially applies to rotating equipment such as pumps. Many faults such as pump and driver misalignment, imbalance of rotating components, worn, loose or damaged parts will cause abnormal vibration of the pump. The level of vibration measured using accelerometers or velocity sensors can be used to indicate the health or integrity of the pump. According to ISO 10816, velocity peak and/or RMS value is typically used for assessing the severity of rotating machinery vibration. When velocity peak or RMS value rises above a threshold, abnormal vibration will be detected. This can be served as a pre-emptive warning for operators to warrant a detailed diagnosis and inspection to rectify the faulty pump. The results are shown in Fig. 16.

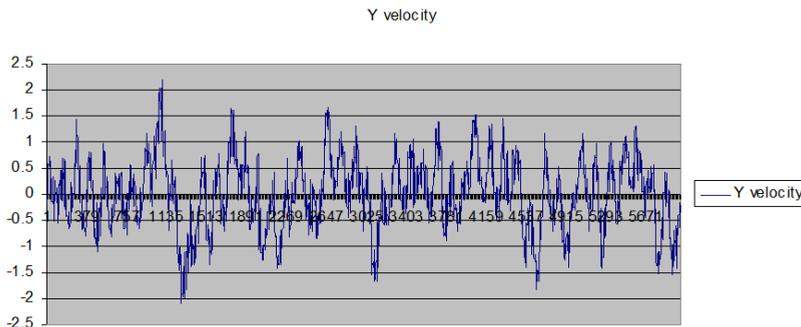


Fig. 16. Velocity Signals from WSN Board

The Jennic sensor node with MEMS accelerometer was used for on-line condition monitoring and status alerting. Using on-board time domain data processing techniques, the peak value and velocity are extracted from a window of high speed acceleration data. An integration algorithm is applied to the acceleration data.

6. Conclusion

The WSN platform has shown its great potential for factory automation applications in the networked manufacturing environment. The future work will extend above models for other types of real-time networked control systems and explore the different control or estimation objectives from these systems. Based on that, more generic model can be explored. Based on the limitation of current approach, several potential research directions are summed as follows:

- **Stability Issues for Control and Communication**
The future work will also focus on stability issues for both sensing and control system and routing of network communication. Some analytical models need to address the robustness issues for control system and networking infrastructure in different time scale.
- **Duality Gap Issue for Non-Convex Cases**
For many cases, even for the deterministic model for the network resource allocation, there exist situations where NUM is non-concave and constraints are not convex

functions and not separable. There is a need to set up alternative model to analyze and reduce the duality gap in order to achieve global optimal solution. It requires more efforts for such conversion which leading a non-convex problem into a convex one. Although, in theory, such approach can resolve duality gap issues however bearing risk of instability and it will be also acceptable to apply gradient programming using dual-decomposition approach leading to the suboptimal solutions however more stable in practical cases.

- Stochastic Model for Networking Data Flows

The future work will also look into stochastic features for the system to reflect more dynamic features of packet flows in the queuing networks especially for WSN. It may require more complex techniques or algorithms to handle the coupling issues of networking constraint functions. It will incorporate stochastic network dynamics at different network protocol layers. This leads to challenging models of queuing networks however it can reveal more details of WSN at communication layers.

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Factory automation has evolved significantly in the last few decades, and is today a complex, interdisciplinary, scientific area. In this book a selection of papers on topics related to factory automation is presented, covering a broad spectrum, so that the reader may become familiar with the various fields, and also study them in more depth where required. Within various chapters in this book, special attention is given to distributed applications and their use of networks, since it is one of the most relevant subjects in the evolution of factory automation. Different Medium Access Control and networks are analyzed, while Ethernet and Wireless networks are looked at in more detail, since they are among the hottest topics in recent research. Another important subject is everything concerning the increase in the complexity of factory automation, and the need for flexibility and interoperability. Finally the use of multi-agent systems, advanced control, formal methods, or the application in this field of RFID, are additional examples of the ideas and disciplines that experts around the world have analyzed in their work.

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