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Remote structural health monitoring systems for next generation SCADA

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Abstract. Recent advances in low-cost remote monitoring systems have made it possible and practical to perform structural health monitoring (SHM) on a large scale. However, it is difficult for a single remote monitoring system to cover a wide range of SHM applications due to the amount of specialization required. For the remote monitoring system to be flexible, sustainable, and robust, this article introduces a new cost-effective, advanced remote monitoring and inspection system named DuraMote that can serve as a next generation supervisory control and data acquisition (SCADA) system for civil infrastructure systems. To evaluate the performance of DuraMote, we conduct experiments at two representative counterpart sites: a bridge and water pipelines. The objectives of this article are to improve upon the existing SCADA by integrating the remote monitoring system (i.e., DuraMote), to describe a prototype SCADA for civil engineering structures, and to validate its effectiveness with long-term field deployment results.

Keywords: structural health monitoring; SCADA system; remote monitoring system

1. Introduction

Structural health monitoring (SHM) is the use of sensing and analytical methods for predicting the degradation and failure of civil infrastructure systems and for preventing the potential associated disasters (Lynch and Loh 2006). SHM is being actively applied to the assessment of civil structures and lifeline systems. However, different systems impose a diverse range of requirements, including the frequency range of interest, monitoring method, data handling, functional partitioning, communication bandwidth, and power demand. Unfortunately, SHM solutions for one class of civil structures are often inapplicable to another class due to the diverse requirements. As two extreme examples, bridge monitoring (Rice *et al*. 2010) is done by *sporadic* monitoring in the low frequency response range, while pipelines monitoring for rupture detection (Shinozuka *et al*. 2010) is done by *continuous* monitoring of higher frequency modes. The computational resource requirements of these SHM applications are very different in terms of memory capacity, data throughput, communication interfaces, etc. In addition, the deployment environments can be harsh and impose additional requirements in order to operate in toxic

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locations, high humidity or extreme temperature range, underground, or underwater settings, such that it would be a challenge to swap the monitoring systems for these two applications.

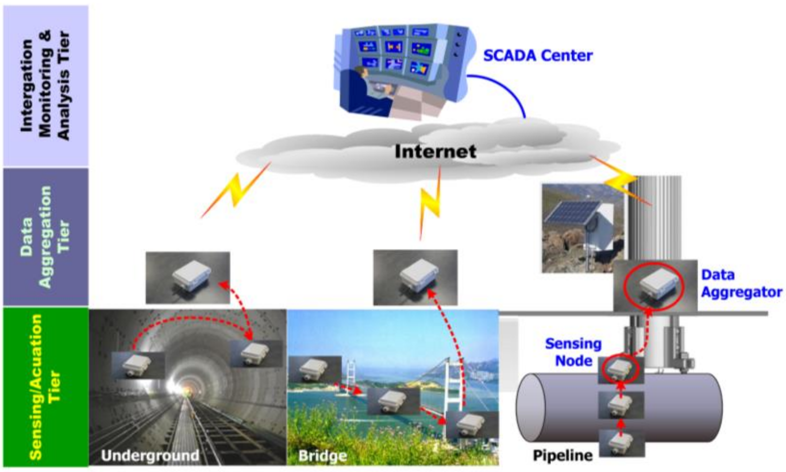


Fig. 1 Proposed Framework for Structural Health Monitoring

Even though it is difficult to design a single monitoring system that can cover a wide range of SHM applications, it is still a worthwhile goal, because it takes a nontrivial amount of work to design a new system each time, especially when many concepts are similar. It is constructive to first identify and scrutinize the subsystems so that those requiring different performance or functionality can be replaced and composed with the rest of the system without having to redesign the entire system.

To have a better chance of covering a wider dynamic range than previous SHM platforms, we studied the properties of two opposite examples of SHM, namely water pipe monitoring and bridge monitoring. Based on their characteristics, we have determined a common SHM framework in which modular components can be plugged in to meet the application-specific requirements while most of the overall framework can be reused. Fig. 1 shows our proposed SHM framework as a 3-tier network. The sensing/actuation tier consists of nodes equipped with various types of sensors and actuators with a communication interface. They are connected to data aggregators in the next higher tier as the data uplink as well as for in-field data processing and storage. Then, the top-level integration Monitoring & Analysis (*i*MA) tier ultimately has the global view of the system being monitored and can control the subsystems accordingly. In such an organization, different options of sensing, communication, and computation resources can be plugged in, making it flexible to serve the requirements of different SHM applications.

For instance, buried pipelines (Kim *et al*. 2011) or underground railways (Bennett *et al*. 2010) require wired connectivity to function properly or for high data fidelity; whereas wireless communication may be easier for the bridge case, depending on the condition of the deployment setting. Each node may support different types of sensors such as accelerometers (MEMS or piezoelectric), inclinometer, humidity, strain, gas, pressure, and temperature sensors. To address the issue, a simple and universal sensor interface should be developed to accommodate various types of sensors with different sampling rates. For instance, bridge monitoring systems need low sampling rate and low data throughput, whereas pipe monitoring system is interested in high frequency response to detect and identify rupture events. To cover both counterpart SHM applications, therefore, the remote monitoring system should be flexible with setting the sampling rate, cut-off frequency, and communication throughput according to application requirements.

SHM systems deployed in the field may run on battery, energy harvesters, or grid power. Grid power is most desirable but not always available in remote or underground locations, so batteries are often used. Different SHM applications can have very different power requirements. For instance, some nodes with very low duty cycle (e.g., collecting data for less than 30 seconds per day) may run for a year on two AA 2000 mAh batteries (Raghunathan *et al*. 2002),whereas others that collect data constantly at high sampling rate with long-range communication may drain a 600 Ah marine battery within three weeks. Batteries all have limited capacity and must be replaced or recharged at some point, but manual replacement may be very costly. As a result, energy harvesters (Park *et al*. 2008) for solar, thermal, acoustic, and vibration sources are being leveraged to supply sustainable power to the nodes. Energy harvesting is particularly difficult for underground sensors, as it is difficult to find sufficient ambient power sources underground with comparable power density to solar (Roundy *et al*. 2003). In some cases, there might not be enough room to fit the potentially bulky battery. In these cases, power must be delivered over transmission lines to the sensing nodes.

2. Related work

Recently, wireless sensor systems not only have been deployed for various SHM applications, but they also have been reported by Lynch and Loh (2006) in various aspects of including data acquisition, embedded computing, wireless channels, and power source specifications etc. Among them, we survey representative SHM systems deployed on cable-stayed bridges and water distribution systems and compare our system with previous ones in terms of diverse application requirements.

2.1 Remote monitoring for cable-stayed bridges

Representative previous studies performed for monitoring of cable-stayed bridges reveal that the natural response frequency ranges from 0.5 Hz to 15 Hz. The Alamosa Canyon Bridge (Lynch *et al*. 2003) located in Truth or Consequences, New Mexico, was instrumented with the 7 wireless modular monitoring systems (WiMMS). A WiMMS is equipped with a biaxial MEMS accelerometer. The prototype WiMMS is powered by a 9 V battery with a 244 Hz sample rate, acquires the acceleration data over a 10-second interval, and computes the acquired data using a high-performance embedded processor. The high power requirement limits the system operation time to only 10 hours on a full battery. Since the WiMMS nodes do not consider energy harvesting, system flexibility, and robustness, they are suitable neither for long-term deployment nor in harsh environmental conditions. Lynch *et al*. (2005) deployed on the Geumdang Bridge improved wireless sensing units with newly added features including time synchronization, local data aggregation, and weatherproof casing. However, its time synchronization is inaccurate, because it is implemented by local wireless beacon signal without consideration for the global clock. Also, the unit is powered by batteries, making it difficult for sustainable operation. Moreover, the higher noise floor of piezoelectric accelerometer compared to that of MEMS accelerometers imposes additional limitation on the sensor units.

As sensor technology matured, Pakzad *et al*. (2008) deployed a total of 64 nodes on the Golden Gate Bridge in San Francisco, California to test the scalability and performance of the WSN. Each node is based on the commercially available MicaZ platform with two accelerometers and one temperature sensor. The target data-logging sampling rate was chosen to be 200 Hz, and the anti-aliasing cut-off frequency was 25 Hz. However, the MicaZ mote experienced the data transmission bottleneck, incorrect estimation of link quality, and frozen routing tree on the Golden Gate Bridge deployment. The purpose of the deployment was primarily the validation of the wireless networking capabilities, but the system did not consider flexibility, waterproofing, or energy harvesting.

Recently, Ho *et al*. (2012) deployed a solar-powered vibration and impedance sensor based on the iMote2 on the cable-stayed Hwamyung Bridge in South Korea. Hybrid SHM capability, solar-powered operation, wireless communication ability were evaluated on Hwamyung cable-stayed bridge. In fact, the sensor system addresses several previous issues including flexible sensor nodes, waterproof enclosure, and energy harvesting. However, the sensor platform is still not suitable for harsh environmental conditions such as underground deployment and real-time monitoring, as it performs high-rate sampling for only a short amount of time per day and takes as much time as needed to relay the data back to the data sink. Furthermore, its energy harvester was inefficient, where the solar panel was directly connected to its battery through a diode without performing maximum power point tracking (MPPT).

2.2 Remote monitoring for water distribution systems

Researchers have proposed the use of WSN for monitoring the performance of water distribution systems to detect any failure or security breaches. Damage events in water distribution networks are characterized by much higher modes of frequency response compared to those in civil SHM such as buildings and bridges. Furthermore, the sensors must be deployed in or on buried pipes underground. Published research approaches varied in their sensing techniques, mathematical formulation, data acquisition methods, and data processing algorithms.

Stoianov *et al*. (2007) presents PIPENET, a prototype tiered wireless monitoring system for hydraulic and water quality modeling, which was deployed at Boston Water and Sewer Commission (BWSC) in December 2004. It has three tiers: Mote tier in manholes, Gateway tier placed on the utility poles, and Middleware & Backend tier at a central office. The Stargate in the Gateway tier consumes high computational and long-range wireless power. Thus, it is powered by a grid with battery backup. The Mote tier consists of a cluster of battery-operated sensor motes with low data storage and performing signal compression and local data processing.

Jin and Eydgahi (2008a) utilizes non-destructive detection technology, Piezoelectric ceramic lead Zirconate Titanate (PZT) sensors, which are mounted on the curved surface of the pipeline for generating and measuring guided waves along the pipes. Kim *et al*. (2008) also introduced a two-tier non-intrusive water monitoring system, NAWMS, which captures the water flow rate using vibration sensors. This system can detect the water flow rate by using non-intrusive vibration sensors similar hardware components to that of Stoianov *et al*. (2007).However, the non-intrusive vibration sensors of the NAWMS can be autonomously calibrated by the correlation between two-tier information.

In another approach, Yoon et al. (2011) proposes Steamflood and Waterflood Tracking System (SWATS) for oil field monitoring to improve the conventional SCADA systems by adopting wireless sensor networks with a decentralized architecture. The key technique of this research is its in-network processing algorithm for the identification of both real and false alarms with a decision tree by collaboratively exploiting spatial and temporal correlations in the sensor readings. Despite of many advanced technologies, since the system is powered by batteries, it is expected to incur high replacement cost to operate.

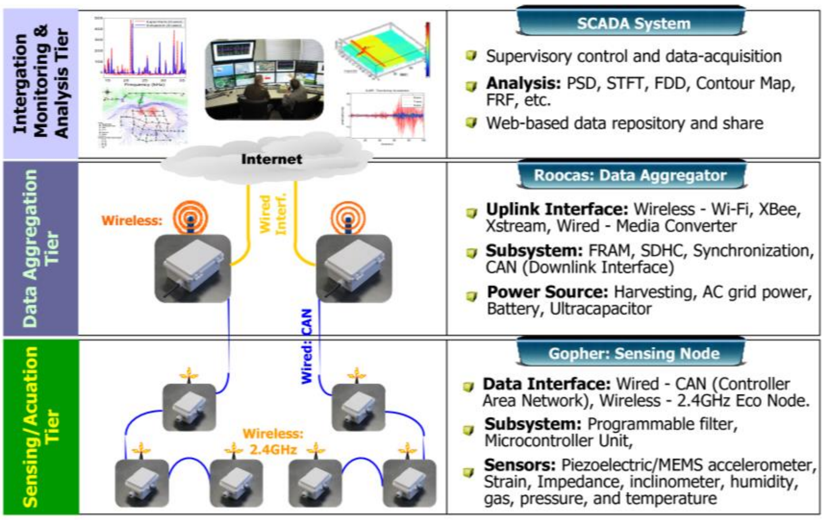


Fig. 2 PipeTECT: Tiered networking system by DuraMote

2.3 Contribution

In this paper, we develop the DuraMote sensing system, consisting of data aggregators named Roocas and sensing nodes named Gopher, to achieve system flexibility, robustness, and power compatibility requirements. DuraMote not only adopts a tiered networking architecture, but it also supports hybrid communication connectivity (i.e., wireless and wired). For the wireless communication, DuraMote can support several different communication technologies depending on communication distance, wireless throughput, and network topology. Since the underground environment makes wireless communication a challenge due to signal losses and high levels of attenuation, wired communications is more reliable to ensure high data quality. Therefore, Controller Area Network (CAN) is utilized as a wired communication medium. With utility power and energy harvesting interfaces, the system can distribute power to daisy-chain connect multiple sensing nodes via CAN bus called Power over CAN (PoCAN). Finally, the performance of DuraMote is validated on two representative civil structures: a water distribution system for high-frequency modes and a cable-stayed bridge for low-frequency modes.

3. Technical approach

To design a system that can work over a wide range of SHM applications, we organize the system into a modular structure such that different subsystems can be replaced to meet application-specific requirements. Our approach is to provide modularity with a tiered architecture and support data processing on this architecture.

3.1 Tiered system architecture

To meet diverse requirements of different SHM applications, our approach is to adopt a tiered system architecture. It consists of the sensing/actuation tier, data aggregation tier, and integration Monitoring & Analysis (*i*MA) tier, as shown in Fig. 2.

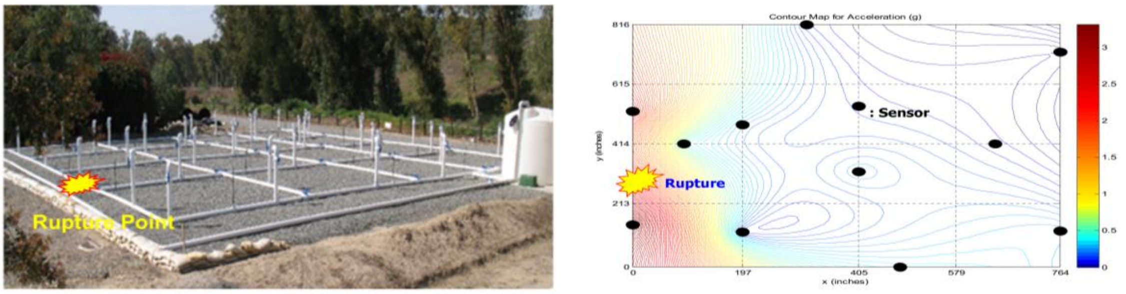
The sensing/actuation tier consists of local networks of sensing and actuation nodes (SAN). They are the direct interface to the physical objects in SHM. Each SAN is equipped with sensors such as accelerometers, humidity sensors, temperature sensors, etc., or with actuators such as motor drivers. Each SAN may include on-board analog-to-digital converters (ADC) for interfacing with sensors or digital-to-analog converters (DAC) for interfacing with actuators, or these sensors and actuators may support a digital interface. Multiple, potentially heterogeneous, SANs may form a local network with each other for collaborative sensing and actuation, or for relaying data. The network may be wireless for convenient deployment, but in case of underground deployment, where radio-frequency (RF) communication does not work well, a wired network may be more practical. The same network may also provide an uplink to the upper tier for data aggregation.

The data aggregation tier consists of networks of *data aggregator* nodes (DAN). A DAN is an embedded computing system capable of performing data logging, in-field processing, or uplink transmission, depending on the specific SHM requirement. Because a DAN aggregates data collected from or distributes actuation data to nodes in the sensing/actuation tier, it means a DAN needs at least two communication interfaces: a downlink interface to the sensing/actuation tier and an uplink interface back to the SCADA center. Multiple DANs can form medium-range nodes for additional data aggregation or data relaying.

The integration Monitoring & Analysis (*i*MA) tier is defined by the SCADA system with the (large-scale) communication network(s) that act as downlinks to the data aggregation tier. The SCADA system can be thought of as the “command center,” where the state of the civil structures under monitoring can be viewed, and commands to actuate the structures can be issued. The SCADA may also make certain data available for broader dissemination. Sections 4 provides detailed features of sub-system components and operation of sensing/actuation, data aggregation, and *i*MA tier.

3.2 Networking topologies among tiers

To show the broader applicability of our approach, there are a number of application examples. Among them, we take one example to present how to configure networking topology between tiers: that is, the application for non-invasive rupture detection and localization of water pipes. This is possible based on the observation that a sudden change such as a pipe rupture and pump stoppage translates into a rapid response of the network particularly in the neighborhood of the source. This suggests that some measurable signature that indicates the rapidity of this change can be used for the purpose of such an identification.



(a) 65’×65’ pipe network (b) Contour Map

Fig. 3 Acceleration-based contour map for rupture detection

An SHM system can be constructed as follows. SANs consisting of MEMS accelerometers with a wired communication interface can be deployed on the exterior surface of underground water pipes, typically at network joints. Specifically, sensors are installed at all the joints in the pipe network so that at least two end joints of every link of the network are monitored. Multiple SANs relay data to a DAN that computes in real-time a measure of acceleration-change or raw data, depending on uplink bandwidth availability. Multiple DANs transmit their raw or processed data back to the SCADA in the *i*MA tier. When a rupture occurs in the network, the sudden disturbance in the water flow and pressure induce the corresponding sudden change in the acceleration of pipe vibration. This change in the pipe acceleration is measured, and on the basis of these acceleration data, the location of the pipe rupture can be found in the pipe segment between the two end joints where the acceleration gradient values form local maxima. This procedure, utilizing the non-invasive measurement of acceleration on pipe surface, facilitates simple, cost-effective identification of the ruptured pipe segment.

We note that the development of the exact correlation between the water pressure and the corresponding acceleration on the pipe surface needs further analytical study assisted by calibration on the basis of tests with small-scale models and in the field using actual water systems. For the field test, we plan to take advantage of scheduled events by the system owner or operator including valve opening and closing, switching on and off the pumps, and water discharge. We intend to make best to develop analytical models for the water pressure-pipe acceleration correlation through these field experiments.

Sensor modules vary depending on the application and technique. For instance, medium to large-sized leakage detection may use time-synchronized pressure and velocity (flow) data (Stoianov *et al*. 2003); sewer line monitoring may require hydraulic and water quality sensors as well as combined sewer outflows (CSO) (Stoianov *et al.* 2006); pipe failure detection may use acoustic/vibration sensors, velocity (flow) sensors, and pressure sensors for measuring transient (Stoianov *et al*. 2007). Pipe leakage may use barometric pressure sensors (Bakar *et al*. 2007) or acoustic sensors (Jin and Eydgahi 2008b). However, the choice of the platform depends on many factors, including power and latency constraints, data rate, and local processing demand.

3.3 Statistical data processing

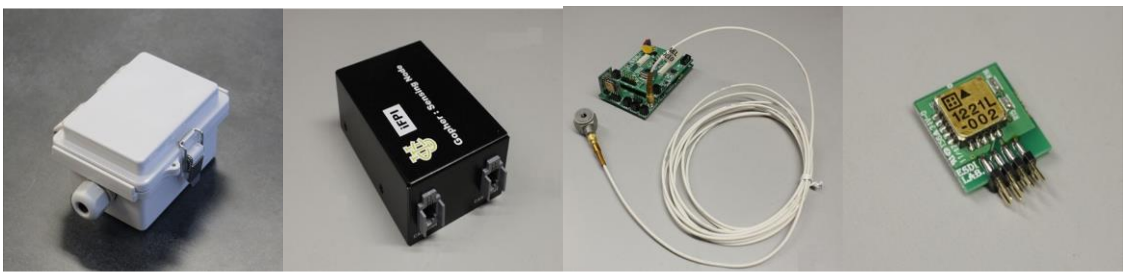
Data processing techniques are crucial to acquiring the efficient computing power for remote sensing systems. Such techniques can be categorized into time-domain analysis and frequency-domain analysis. Time-domain analysis is a simple way to detect and identify sudden damage of civil infrastructure with low computational complexity. For this reason, based on the theoretical correlation in Shinozuka *et al*. (2010)

$$dp = \left(\varrho - \frac{4E}{D^2 \omega^2} \right) ta \tag{1}$$

where *dp* is the pressure variations, ϱ is the mass density of the pipe, *E* pipe's elastic modulus, *D* is the pipe diameter, ω is the angular frequency, *t* is the pipe wall thickness, and *a* is the acceleration we plot a contour map for the convenience of visualization to localize the damage on the water pipe network with time-domain acceleration data as shown in Fig. 3.

However, the time-domain data analysis is not always possible to tell apart smooth structural deterioration events from substantial white noise due to ambient excitation. Thus, in such small event case, frequency-domain analysis would be useful to detect or identify a small degradation event. For modal analysis in frequency domain, frequency domain decomposition (FDD) has been receiving growing attention in recent years for output-only system identification due to ambient excitations in the frequency domain. Therefore, we adopted the FDD analysis to detect and localize damage of civil infrastructures. In FDD analysis, the first step in system identification is estimation of PSD matrices of the output signals. The PSD matrix at each discrete frequency, ω_i, can be directly estimated by taking the Fouriertransform of the cross-correlation matrices of the output signals. Estimated matrices can be decomposed by applying singular value decomposition (SVD) technique

$$\hat{Y}(j\,\omega_i) = U_i\, S_i\, \overline{U_i} \tag{2}$$



(a) for Outdoor, (b) for Indoor, (c) PCB w/PZT and (d) Pluggable sensor

Fig. 4 Gopher: Sensing Node in the sensing tier where U_i is the matrix of singular vectors, and S_i is the diagonal matrix of the singular values. If only one mode is dominating, the first singular vector is an estimate of the mode shape, and the area in the vicinity of the corresponding singular value is the auto-PSD function of the associated single degree of freedom (SDOF) system. Therefore, the FDD analysis results have been reported to be significantly more accurate than the results of the classical frequency-domain approach.

4 . System implementation

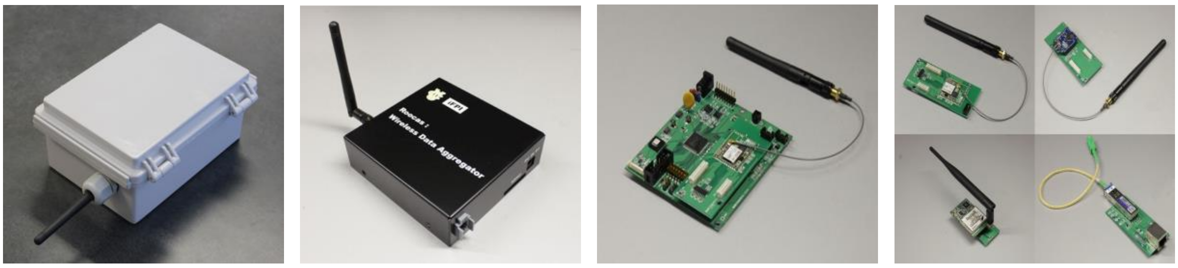
This section describes the subsystems that we designed for each of the sensing/actuation, data aggregation, and integration monitoring & analysis tiers.

4.1 Sensing/Actuation node

Our sensing/actuation node is named Gopher, as shown in Fig. 4. It is designed to support a variety of sensors, actuators, signal conditioning, and short-range (i.e., 10～50 m) communication in the sensing/actuation tier.

For most SHM applications, including water pipe monitoring and bridge monitoring, acceleration sensing is used. Therefore, we design the Gopher node with up to three axes of high-precision MEMS accelerometers, plus one expansion port for the connection to other types of sensors such as a piezoelectric accelerometer as shown in Fig. 4(c). One MEMS accelerometer is on the Gopher board, while the other two are of a pluggable type with sockets (Fig. 4(d)). This way, we can adjust the number of axes from one to three to meet the requirements of different applications. In addition, an 8-channel ADC with 10-bit resolution is built in the microcontroller on a sensing board to connect other sensors such as humidity, temperature, gas, strain, etc. A user-adjustable digital filter (QF4A512) is a main distinguishing feature of sensing nodes to achieve high data fidelity by signal conditioning. The signal conditioning can reduce aliasing error and analog-to-digital conversion noise. For this purpose, Quickfilter QF4A512 is suitable for sensing nodes to achieve the high data fidelity.

Gophers support both wired and wireless communication interfaces. For wireless connectivity between Gophers and as uplink to the data aggregator, we use the ultra-compact wireless sensor platforms named Eco, EcoSpire, and EcoSD (Chou 2011),which can work as either a self-contained sensor node or as a wireless plug-in module. It supports short-range RF communication of up to 10 meters at 2 Mbps and can form a very dense network of up to hundreds of nodes in a small area. Wired communication is also supported for use in harsh environmental conditions, such as underground or underwater settings. We choose the Controller Area Network (CAN) protocol as the data link among multiple Gophers as well as the uplink from the sensing/actuation tier to the data aggregation tier. CAN is a low-complexity, high-throughput wired bus that can support real-time scheduling and reliable data transmission, and the robustness of CAN has been proven in the automotive field and in industrial control. Theoretically, up to 100 Gophers can be daisy-chained on the CAN bus to a data aggregator (Section 4.2). We also support power over CAN (PoCAN) by running supply power lines alongside the data wires to power multiple Gopher nodes. This is particularly useful for powering nodes deployed underground.



(a) for Indoor, (b) for Outdoor, (c) PCB and (d) Comm.modules

Fig. 5 Roocas: Data aggregator in the aggregation tier

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4.2 Data aggregator

Our data aggregator node is named Roocas, as shown in Fig. 5. It contains the processing, storage, and communication links to support all data aggregation tasks. Roocas serves as a cluster head to the sensing/actuation tier. It collects measured data from multiple sensing nodes via CAN interface or wireless relay. It can process the data (filter, transform, compress, etc) in software, and it can log data into its flash memory card as needed. It provides several options for its data uplink. This subsection describes its communication interfaces and its enclosure.

Roocas includes communication interfaces for both downlink to the sensing/actuation tier and uplink to the *i*MA tier. The downlink interfaces include both CAN and Eco, the same as those found on Gopher (Section 4.1). The uplink interfaces of Roocas include three wireless and one wired: XStream, XBee Pro, Wi-Fi (default), and Ethernet (10 Base/T to 100 Base/FX media converter). They are designed as a stackable structure, which can be easily configured to meet the specific application requirements, including the communication range, data rate, and power. For data streaming, Wi-Fi or Ethernet is chosen for the high data rate depending on its availability. Wi-Fi connectivity offers several advantages, including easier installation compared to Ethernet, and better power efficiency, higher data rates, and world-wide license-free operation compared to the other two wireless interfaces. The XStream module provides up to 32 km of wireless data communication range in direct line-of-sight when used in conjunction with a high-gain antenna. The throughput of the XStream is 19.2 kbps, whereas the XBee Pro supports 156 kbps of RF data rate with a range of up to 1.6 km as mentioned in Section 1. These longer-range wireless modules have lower data rates than the shorter-range ones do, making them more suitable for cases where wired or wireless Internet coverage is not available. The lower data bandwidth of these longer-range interfaces means they should apply event-driven monitoring methods rather than data streaming. DuraMote can support both event-driven and data-streaming types of applications.

For outdoor deployment, we consider enclosures with protection against windblown dust, rain, splashing, and hose-directed water. In addition, the enclosure of DuraMote system has several knockouts for power and data cable connection. This knockout port is also designed to protect the system against harsh environmental conditions as shown in Figs. 4(a) and 5(a) for outdoor deployment and indoor (Fig. 5(b)). The four types of data communication technologies are shown in Fig. 5(d).

4.3 SCADA system

The main component of *i*MA tier is the *supervisory control and data acquisition system* (SCADA), a computer system for gathering and analyzing data collected from lower tiers and controlling them. In general, SCADA systems are used to monitor and control factories, industrial equipment, clean and waste water processing, power generation facilities, oil refineries, and transportation networks.

To acquire the data or status from the data-aggregation tier more flexibly, the developed SCADA system (i.e., next generation SCADA system) can support various communication connectivities: Wi-Fi, WiMax (Worldwide Interoperability for Microwave Access), WiBro (Wireless Broadband), LAN (Local Area Network), and cellular phone interfaces along with conventional Public Switched Network (PSN). Accordingly, the system is applicable to various civil infrastructures. The design goal of a user interface is to build global and detailed views of the state of the civil infrastructure systems. The SCADA server displays the acquired data via a web browser. The geographical locations of each sensing system are established based on Google Map. By clicking on one of the deployed locations, the user can see the analysis results in time- and frequency-domains with information about the deployment site. This user interface is written for common web browsers, so it can run on conventional computers and hand-held devices. This web-based user interface enables prompt status monitoring and management by the supervisory control center and field engineers.

The SCADA server uses advanced statistical analysis modules and system identification algorithms for damage identification. In time domain, three simple statistics modules are used: the *running variance*, the *windowed gradients*, and the *min-max difference*. The running variance helps to differentiate between noisy and smooth signals. On the other hand, windowed gradients can identify sharp drops and rises in pressure data (i.e., transients), and max-min difference is useful to identify smoother signals with abnormal spikes. In frequency domain, the data are analyzed with complex but more powerful algorithms such as *frequency domain decomposition* (FDD), *subspace identification* (SSI), and *frequency response function* (FRF). Frequency domain decomposition is a computationally expensive algorithm that identifies the eigenvalues and eigenvectors of *n* signals.

Brincker *et al*. (2001)takes advantages of Fast Fourier Transform and correlation between signals to identify the modal properties of the system. In civil engineering, it is used to identify the natural frequencies and mode shapes of a structure. Subspace identification is another powerful algorithm to identify the modal properties of a system (Cho *et al*. 2010). The performance of these two algorithms is compared and evaluated by Yi and Yun (2004) and Ulusoy *et al*. (2011). Every module and algorithm can be activated or deactivated by users’ demands.

(a) Bay Bridge Pump Station (b) Vault site near Bay Bridge

Fig. 6 Photo of OCSD deployment

5. Field experiments: pipeline and bridge

Two deployment sites are considered as the representative extremes for validating the ability of the DuraMote sensing system to cover a broad range of SHM applications. The first site is administered by Orange County Sanitation District (OCSD), whose sewer pipelines require high frequency mode monitoring. The other is Vincent Thomas Bridge (VTB), a large suspension bridge requiring monitoring of low (sub-Hz) frequency range. Additional features such as power adaptability between utility power and energy harvesting, system flexibility, and robustness are also validated in these field tests.

Table 1 Tasks schedule for OCSD (2010～2012)

Date	Site	Location	Tasks
March 31, 2010	BBPS & VBB @ OCSD	Newport Beach, CA	Battery power, Data logged
March 24, 2011			Battery power, Long-haul AP, Wi-Fi, xDSL
March 15, 2012			Solar+Battery power, xDSL, 3G cellular network

5.1 OCSD: Sewer pipe monitoring

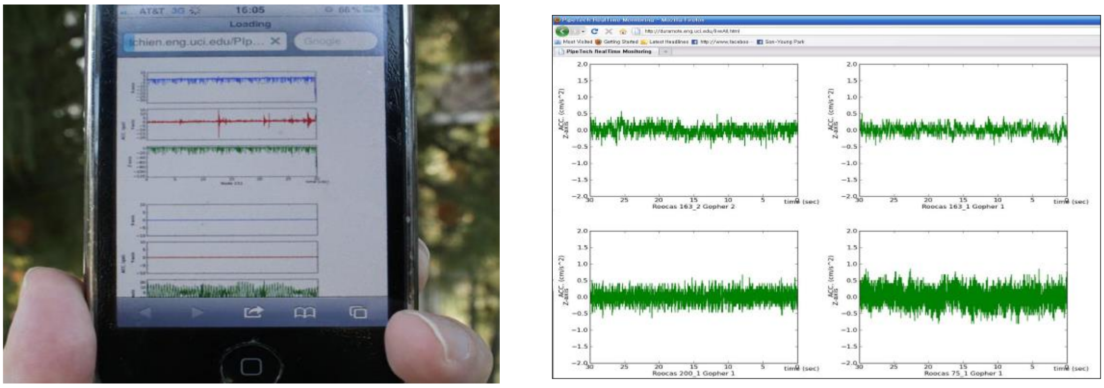
Fig. 6 shows the deployment of the DuraMote sensing systems at the Vault by Bay Bridge (VBB) and the Bay Bridge Pump Station (BBPS) of OCSD. They are chosen for the analysis of pressurized sewer pipes.

5.1.1 Site descriptions

***The Bay Bridge Pump Station*:** The BBPS is located in the County Sanitation District 5 building visible from Pacific Coast Highway (PCH). It houses the generator, pumps, and pipes. This site has utility power and is furnished with a DSL line for Internet connection to send the aggregated data back to the server at UC Irvine. The basement level of the station is where the pumps and the four pipes are located. Fig. 6(a) shows the details of the pump station. Sewage is pumped up and out (to the left) of the pipes shown in the figure, and therefore sensing nodes are deployed on the top side of the horizontal part of these pipes. Note that the Gopher nodes are connected by wires for data and power to one Roocas data aggregator, which in turn uses its Wi-Fi interface to connect to the access point attached to the Internet uplink.

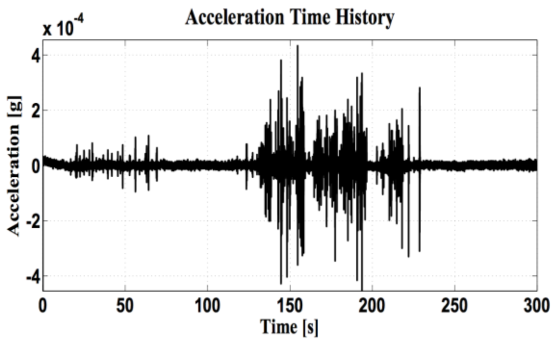
***Vault by the Bay Bridge*:** Fig. 6(b) shows the VBB, which is 500 m away from the BBPS. Sewage from the pump station is split into two pipes that run along the street towards the treatment plant. Sensors can be deployed on top of these two pipes, similar to the topology at the BBPS. This site is useful to evaluate the remote sensing system in terms of low noise figure of MEMS accelerometers, algorithms for detecting pressure waves due to the *water hammer* effect, long-haul wireless communication, and the remote access capability from the SCADA center at UC Irvine.

This site has neither utility power nor wired Internet connection. In this case, the Gopher (sensing) nodes inside the vault are connected by wire for data and power to the Roocas (data aggregator) node outside the vault through a hole drilled on the vault cover. The Roocas is in turn connected to the long-range Wi-Fi relay to transmit the aggregated data through the Internet uplink at the BBPS back to the SCADA server at UC Irvine. If the Internet uplink is not available, then a cellular modem can be used instead. The system was initially powered by two 600 mAh marine batteries, but it lasted only several weeks. Instead of replacing batteries, which would be costly, we installed a solar panel next to the vault to take advantage of the plentiful solar energy in this climate.

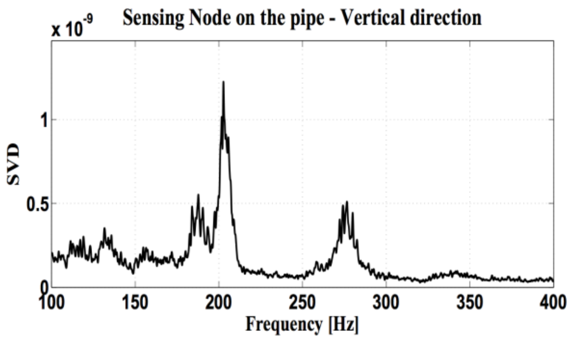


(a) Mobile phone monitoring (b) Web-based monitoring

Fig. 7 Photo of OCSD deployment



(a) Time history of vault at OCSD



(b) Frequency domain of vault at OCSD

Fig. 8 Data Analysis in time and frequency domain

5.1.2 SCADA system for pipe monitoring

The acceleration-based SCADA systems was tested three times on March 31, 2010, March 24, 2011, and March 15, 2012 between the BBPS and the VBB as shown in Table 1. The purposes of these field experiments were to identify specific locations, designate appropriate sensors, secure sources of power, select the proper antennas, prepare the enclosures, and to fine-tune the communication in direct line-of-sight. These two field experiments were composed of two main tasks: the raw data collection and the wireless communication range test.

The first experiment entailed raw data collection and analysis. The purpose was to determine the signature of known events such as the process of turning on a pump or turning off a valve. This way, they can be clearly distinguished from potentially abnormal events such as malfunctioning of pumps and pipe ruptures.

The second task was to explore the long-range and short-range wireless communication at this site. To recall, long range means 500 m to several kilometers in this range between an aggregator and data uplink. Short-range communication, on the other hand, means under 10 m between the AP (outside the vault) and wireless modules of the data aggregator (inside the vault) at VBB. We tested several candidate technologies, including Xstream, XBee, a Wi-Fi module, and a Wi-Fi access point (AP) with a high-gain antenna. Based on our exploration of wireless communication range, as well as wireless data throughput consideration, we adopted AP-to-AP topology for the long-range wireless communication between the BBPS and VBB. Consequently, for the short-range communication of AP-to-Roocas, Wi-Fi communication was selected.

In the latest experiment on March 15, 2012, a web-based SCADA monitoring system and a solar energy harvester were added as shown in Fig. 6. The solar harvester consisted of a 20 W multicrystalline silicon solar panel (SX320 by BP Solar) and EscaCap, the supercapacitor-based harvesting circuitry with built-in *maximum power transfer tracking* (MPTT) (Kim and Chou 2011)function for sustainable operation. At the network level, Roocas in the aggregation tier collected data from multiple Gophers in the sensing/actuation tier and then transmitted the data back to SCADA server. The SCADA server plotted the collected data to be displayed as web graphics. In this configuration, live pictures were generated every 500 ms, while the associated web page was automatically refreshed every three seconds. User could also remotely access the monitoring web page via mobile or PC as shown in Fig. 7. In particular, mobile web applications essentially have just two different caveats: a smaller screen size and less robust browser capabilities. However, mobile monitoring function would be helpful in enhancing users' convenience and an emergence management.

5.1.3 Results and analysis

Fig. 8(a) shows a five-minute window of the time history of the acceleration recorded at the BBPS. In frequency domain, the range of interest is between 100 Hz and 300 Hz. The sampling frequency during this experiment was 1 kHz. Fig. 8(b) shows that the first singular value is the result of FDD algorithm, which invokes FFT with a cut-off frequency of 300 Hz and 8 Hamming windows with 50% overlap. The signal does not have any peak in normal operational condition in either time domain or frequency domain. However, when a transient happens inside the water pipe, the pressure wave causes a high-frequency pulse at the cross-section of the pipe where the sensor is placed. This high frequency impulse can be identified both in time domain and in frequency domain as shown in Fig. 8.

5.2 Vincent Thomas Bridge

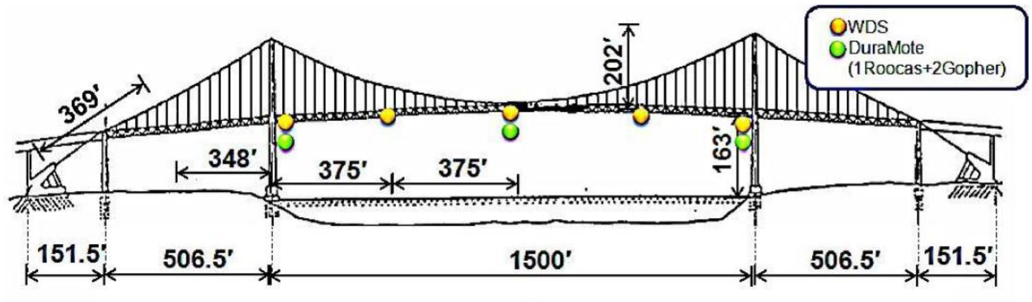
We selected the VTB site as a test site, shown in Fig. 9(a), for evaluating the wireless performance of data aggregators with a relaying network topology as a way to combat circumstantial interferences from the metal structure. A metal bridge is subject to various vibration excitation sources due to traffic loads, wind, and water flow. Moreover, a water pipe is located below the bridge. This makes it a hybrid SHM problem, since the system must be able to pick up both low-frequency components for the bridge itself and the high-frequency components for the water pipes.

5.2.1 Deployment description

Three DuraMote sensors were used in this test and placed in a symmetrical configuration, with one in the middle and the other two approximately halfway between the towers and the center of the bridge. The left side of Fig. 9(a) shows the DuraMote installation on the VTB. Each DuraMote consists of one Roocas and two Gophers, and therefore one Gopher is placed on the pipes of the bridge and the other on the steel box girder of VTB. We used WDS-enabled (Wireless Distribution System) APs 100 meters apart to form a local wireless-relaying infrastructure using relatively small and light antennas. Totally three Roocas, six Gophers, and five WDS APs were deployed as shown in Fig. 9(b).

Table 2 shows the number of packets transmitted by each Roocas on the bridge and the number of packets received by one single AP during the experiment. The packet drop rate is the ratio of the difference between two to transmitted packets from each Roocas. In this network topology, the packet drop rate is below 0.5%. This is considered reliable enough for high-fidelity data acquisition from VTB.

(a) Photo of VTB (left) and installation sensors on the decks and a pipe (right)



(b) Sensor layout on the VTB

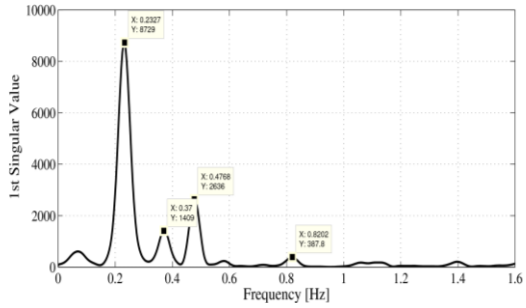
Fig. 9 Deployment of DuraMote on the Vincent Thomas Bridge

Table 2 Packet drop rate from three Roocas on the bridge

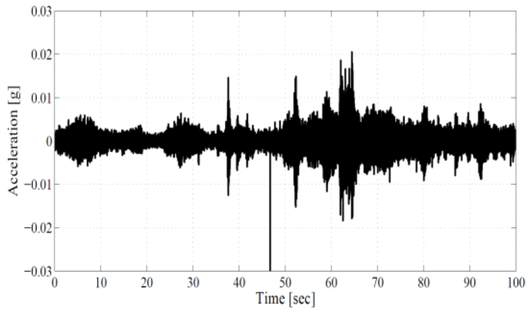
Location	Transmitted Packets from Roocas	Received Packets to Base station	Packet Drop rate
Middle	649,580	648,315	0.19%
Right side	639,192	636,272	0.45%
Left side	626,261	624,047	0.35%

5.2.2 Results and analysis

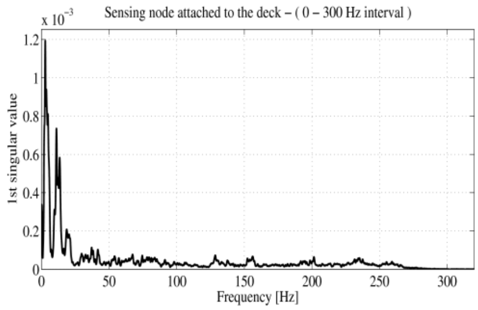
The acceleration data were recorded on the server at the bridge for two hours from every sensing node, and then each channel was analyzed in both time domain and frequency domain at a later time. The sampling frequency during this experiment is 1 kHz and the cut-off frequency is 300 Hz. Frequency Domain Decomposition (FDD) is used to analyze the data in frequency domain. FDD, which was first introduced by [3], is output-only methods to identify the modal properties of a system, which means the modal parameters can be estimated without knowing the input source exciting the systems. Using the FDD technique, we estimate the first singular value of the cross power spectra density matrix at each ω_i . In the matrix, the diagonal elements are the auto-correlation of the signals in frequency domain; that is, the square of the Fast Fourier Transform (FFT) of the signal at ω_i. The off-diagonal elements of the matrix are the cross correlation of two signals also in frequency domain (i.e., the FFT of the first signal at ω_i is multiplied by the complex conjugate of the FFT of the second signal at ω_i). In structural health monitoring, FDD produces exact results if the input signal is white noise, the structure is lightly damped, and the mode shapes that are close to each other are geometrically orthogonal.



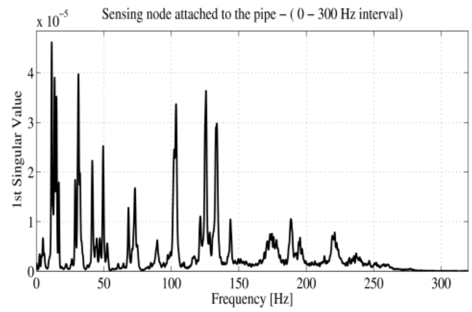
(a) 1st singular value on the deck



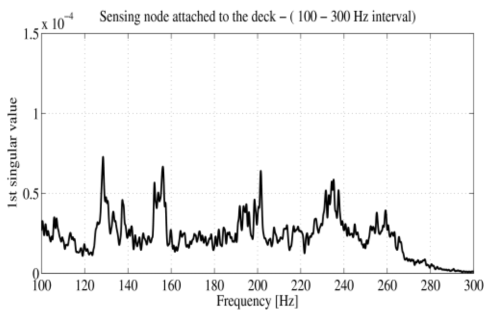
(b) Time history on the pipe



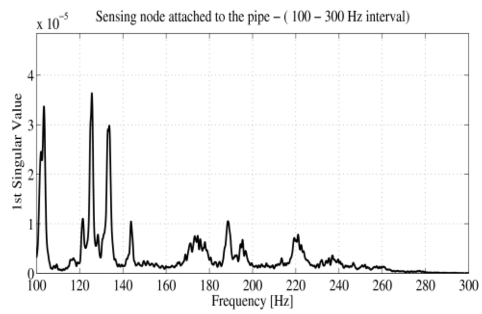
(c) Gopher on the deck 0～300 Hz



(d) Gopher on the pipe 0～300 Hz



(e) Gopher on the deck 100～300 Hz



(f) Gopher on the pipe 100～300 Hz

Fig. 10 Data analysis of the deck and pipe on Vincent Thomas Bridge

Fig. 10(a) exhibits the first singular value from FDD of the three Gophers attached to the deck of the bridge, and Fig. 10(b) shows the time history of acceleration collected from a Gopher on the water pipe. In these figures, the natural frequency along the vertical direction of the bridge can be clearly identified. Fig. 10(c) presents the frequency-domain analysis result from the Gophers on the deck; the natural frequencies of the bridge are dominant from 0 to 2 Hz, whereas Fig. 10(d) indicates the frequency components from the vibration of the water pipe. The frequency contents from the water pipe of the demonstrate further by zooming in on the 100～300 Hz frequency range.

Through the experiments, we have validated that DuraMote is a flexible sensing system: the sampling rate, cut-off frequency, and communication throughput can be adjusted depending on SHM application requirements. In other words, DuraMote is able to cover a wide range of SHM applications.

6 . Conclusions

We have described the latest development of the DuraMote system, including Gopher sensing nodes and Roocas data aggregators. We validated its performance by two representative field experiments: sewer pipelines at OCSD and Vincent Thomas Bridge. The DuraMote system has achieved high sampling rates (1000 Hz) with simultaneous data logging and data transmission for the water distribution system monitoring, as well as low sampling rate with reliable data transmission with a higher power efficiency for SHM of the suspension bridge. We found DuraMote sensing system to have a lower noise floor by an order of magnitude and a wide range frequency response that can cover not only water pipe monitoring but also structural health monitoring. Our tiered networking topology and SCADA server architecture were operational for real-time data upload, viewing, and control over either the Internet or cellular network. The experimental results confirm that our system is a promising step towards a flexible, scalable, robust SCADA system for civil structures.

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List of Symbols

SHM	Structural health monitoring
SAN	Sensing/Actuation Node
*i*MA	integration Monitoring & Analysis
MPPT	Maximum Power Point Tracking
PSD	Power Spectral Density
FDD	Frequency Domain Decomposition
SSI	SubSpace Identification
SDHC	Secure Digital High-Capacity
ADC	Analog-to-Digital Converter
SVD	Singular Value Decomposition
Wi-Fi	Wireless Fidelity
WiBro	Wireless Broadband
VTB	Vincent Thomas Bridge
SCADA	Supervisory Control And Data Acquisition
DAN	Data Aggregation Node
MEMS	MicroElectroMechanical System
FFT	Fast Fourier Transform
STFT	Short Time Fourier Transform
FRF	Frequency Response Function
FRAM	Ferroelectric Random Access Memory
CAN	Controller Area Network
DAC	Digital-to-Analog Converter
PoCAN	Power over CAN
SDOF	Single Degree Of Freedom
OCSD	Orange County Sanitation District
WDS	Wireless Distribution System