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On Architecture of Low Power Wireless Sensor Networks for Container Tracking and Monitoring Applications

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Abstract— **Almost 90% of the world trade is accomplished with the help of containers using different means of transportation including ships and trains. The container trade faces a lot of challenges comprising of container tracking, real time monitoring and intrusion detection, real time theft reporting mechanism, and reporting status of shipment items. While in principle the above functionality can be provided by a state of the art industrial monitoring system, it does not provide the advantages in flexibility and cost of Wireless Sensor Networks (WSNs). In combination with GSM and GPS/Galileo technologies, WSNs can result in a system capable of tracking and monitoring of containers in the real time. This paper discusses the problems faces by the container industry and how a wireless sensor network can deal with these problems.**

I. Introduction

T*ODAY some 18 million containers are constantly crisscrossing the seven seas. These standardized receptacles have become the building blocks of the global village* [1]. Almost 90% of the world trade is done with the help of containers in affiliation with different means of transportation including railways, air, trucks and ships [2]. In other reference [3], the number of containers moving across the globe is more than 100 million amounting to billions of dollars industry.

Container trade has a huge impact on global economy [1, 2, and 3]. Any disruptions to container trade at any time affect the world economy very adversely. According to one case study [4] by Congressional budget office, US congress, the shutdown of ports of Los Angeles and Long Beach would cost US economy somewhere in the range of 455 million to 1050 million dollars per week. Apart of monetary loss on state level, it will also affect a lot of individuals including people working on the ports, the exporters and importers of containers, the container owners and many more. On a lower scale individual containers may contain goods worth million of dollars. On an average it takes a couple of months for the good to be delivered by ship to other parts of the world. Lets assume that the goods are already damaged, while being loaded, so once these goods reach the destination, it would result in a problem for the producers and consumers both resulting in huge losses in monetary terms. By the knowledge that the goods could have been damaged, the company could immediately react and send other goods on the way.

The paper is organized as follows. Section II, gives an overview of related work. Section III, provides issues faced by the container industry. Section IV presents the proposed solution. Finally, Section V gives an outlook of expected implementation results and future work.

II. Related Work

Secure Trade Line [5] proposes a solution for making containers secure and predictable. They have came up with a device called TREC, mounted on container door with different sensors including light, temperature, humidity, acceleration and position sensors. TREC can be configured with a handheld, and is capable of GSM communication. It also supports satellite communication where GSM is not available. It uses ZigBee for short range communication. (between TREC and handheld for example). Our solution differs from [5], in many ways. Firstly TREC is a commercial product by IBM and every thing is not available to the research community. Secondly it uses only one device per container and may not be able to report status of the shipment items within a container. Thirdly, each device per container is directly connected with the GPS system and is more energy consuming as opposed to our proposed solution where we intend to implement local GPS as long as container monitor is in contact with the prime monitor to save energy.

WiFi Smart Chip Tags (WFSCT) is another propriety solution by WiFi, Wireless Inc [6]. The system claims to provide real time container identification, temperature monitoring, cargo tempering reporting, and hazardous and explosive material detection. Being a propriety solution like TREC, no detailed information is available to the best of our knowledge. On abstract level, it resembles our Container Monitor but the concept Internal Monitors is still lacking for the detailed monitoring of the container goods within the container.

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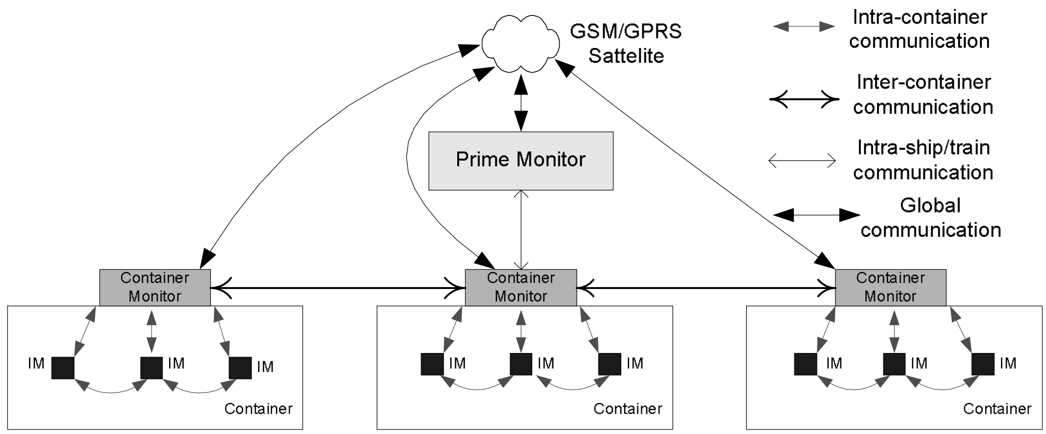

Figure 1: Overall System Architecture with possible communication links

III. Problem Faced by Container Industry

The problems faced by container trade industry are manifold which are summarized below and are discussed in detail in [7, 8].

- Container tracking from the point of loading to the point of unloading on different modes of transport (inter-modal transport)
- Real time risk monitoring and intrusion detection
- Real time theft reporting mechanism
- In time reporting of damage to the shipment containers (current condition and status), so that the container items can be ordered again in time to save cost and time.
- Long life container tracking and monitoring system (Over all low energy system) by use of ultra low power schemes and complimenting it energy scavenging techniques (from vibrations for example which are present all the time while the container is moved from one place to another)
- Low cost and reliable hardware operating in a harsh environment.
- Availability of container information to all the stake holders of the shipment.
- Detection of contra-band materials including explosives with chemical sensors
- Ease of installation and flexibility to add and remove sensors on an as-needed basis.

IV. Proposed Solution

Wireless sensor networks comprising of distributed low cost sensor nodes, when applied to its full capacity can be useful to many application scenarios including container tracking on seaways and railways. The system comprises of Internal Monitors (IM), Container Monitor (CM), and Prime Monitor (PM). Basic IM would be a sensor node. The self/remote configurable IM's are to be place in the containers, which would be used to sense, gather and communicate the "require data" to a more powerful unit, the CM for further processing. Each container has one CM, which either communicates directly with the global communication network or is used for the communication with the PM, if available. The PM is only one per ship or train and acts as an infrastructure node used to connect with the global internet and the Global Positioning System (GPS) where communication of each container would be to expensive in terms of cost and energy or not possible at all as on the world's see. The System architecture is shown in the Figure 1. The Context ontology (inspired from [9]) for the proposed solution is given in Fig. 2.

A) *Internal Monitor*

Internal Monitor (IM) is the basic unit of wireless sensor network. IM is basically a sensor node comprising of different software (MAC, routing, error detection) and hardware (Memory unit, processing unit, power supply unit, AD converter, microprocessor and group of sensors) as shown in Figure 2.

Each IM consists of a group of sensors to gather the data from within a container. Group of different sensors with example scenarios (possible outcomes on basis of contextual data) are discussed in Table 1.

B) *Container Monitor*

Container Monitor (CM), one unit per each container is a device capable of gathering data from the IM's and sending it to the PM directly or to other CM's as they may have a path towards the PM which has a virtually unlimited amount of energy. Still, each container monitor comprise of a GSM and GPS receiver which are used in case when there are no other lower energy paths towards the global communication infrastructure. When there is no PM but a number of CMs which build up a local network, they can elect on an ad-hoc

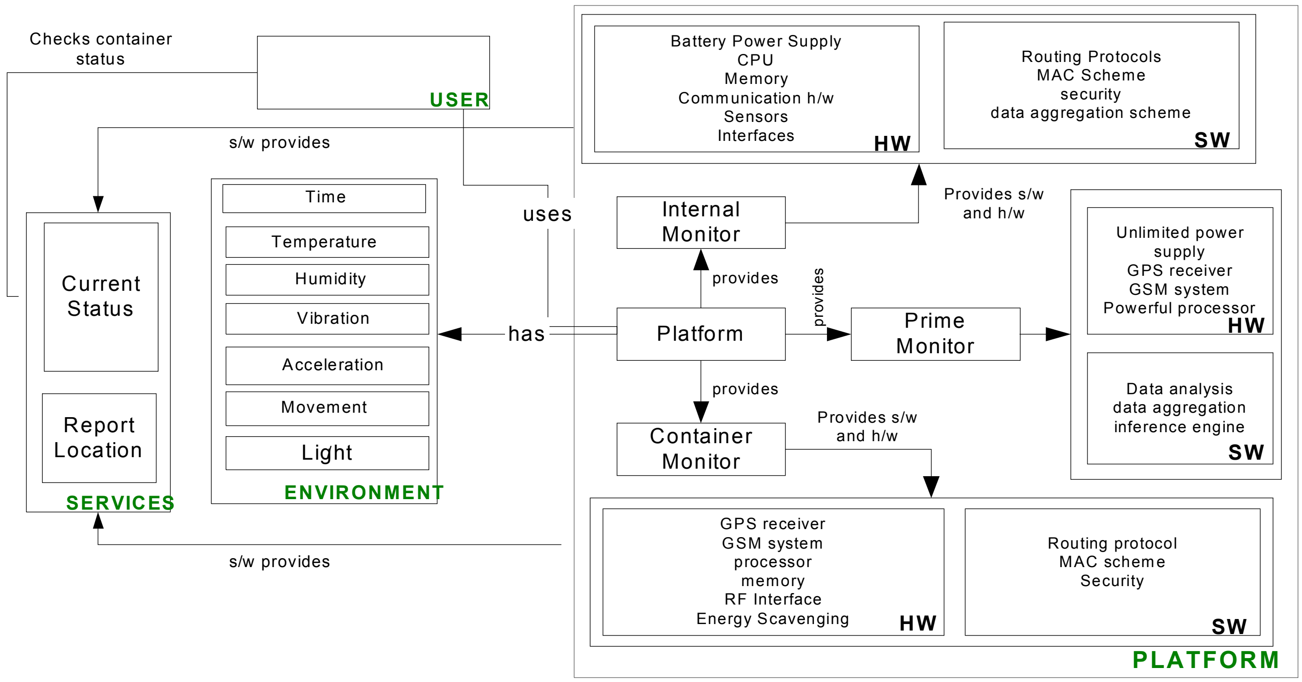

Figure 2: Context Ontology for Container Tracking and Monitoring Application

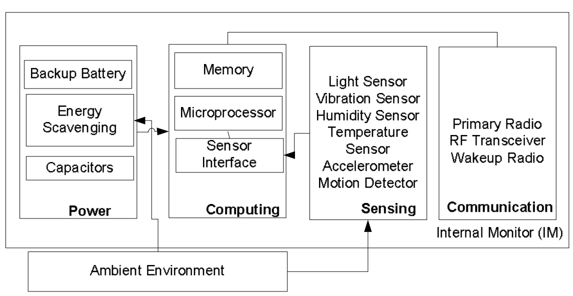

Figure 3: Internal Monitor

manner a communication master which acts as a gateway to the GSM network and is the only node receiving GPS information which then is distributed over the local network. The energy savings in this way can be significant since local communication is more energy efficient then global communication.

The container Monitor has also a large logging memory (SD-Card type or the like, up to Gbytes of storage capacity) which tracks all relevant data, specifically acceleration profiles in all 3-axes as required by certain transports to guarantee quality of transport.

C) Prime Monitor

Like CM, Prime Monitor (PM) has global connectivity (satellite connection) and global location awareness but unlike CM, it is provided with unlimited source of energy and is only one unit per ship/train (not considering backup PM's that would be used to make the overall system fault tolerant). In this way, most of the energy consuming communication is done via PM if available.

Sensor Group	Signal level	Contextual information
Temperature	Temperature is very high	Chances of fire
Humidity	Humidity is high	Water is going into the container
Accelerometer	Acceleration is low	Normal situation
Vibration	Vibration is above certain threshold	Chances of damage
Light	Light intensity is high	Container is opened
Motion	Motion is detected	Some body is inside

Table 1. Group of sensors in IM

This added flexibility with the availability of a PM comes at a price, however in many cases a PM is installed on the head of a train or on the ship anyways for real-time train or ship tracking. It is important to state that the system adapts itself to the possible best configuration by discovering the available devices and choosing the appropriate communication topology.

D) State of the art Sensor Node Platforms

Academic community has developed many sensor nodes platforms ([13]-[18]) which can be used for in-container communication. The actual lowest power solutions still come from proprietary solutions; however standards such as

IEEE802.15.4 including the ZigBee protocol stack [19] will also provide a viable solution due to the fairly simple in-container network topology which is typically a start topology.

Very critical is the use of very low power sensors and the way these sensors are operated. Sensors with very low duty cycle such as temperature do not affect the overall power consumption if turned off completely after measurement, but sensors that track the acceleration profile cannot (or at a very limited basis) be turned off efficiently and need to track on a continuous basis affecting the overall power consumption significantly.

E) Difference between container tracking for Rail Cargos and Ships

In ships and train cargos the shipment containers are arranged differently. Trains contain containers in sequential sort of order, while most containers in the ship are covered from above, below and sides by other containers as shown in Figure 4. Containers in ships poise unique challenges. Big ships have 6 to 7 containers placed over one another and than each bunch of containers are separated by a ship floor (obstructing communication), so additional devices would be required to keep the communication alive.

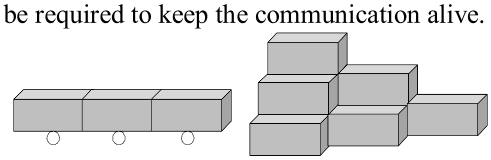

Figure 4: Container arrangement in rail cargos and ships

V. TECHNICAL CHALLENGES

A) Selection of Frequency

According to the laws of physics, lower the frequency, lower would be the attenuation of the radio signal [10, 11] but given the fact that the containers would be used for global trade, so in order to tackle the issue of worldwide compatibility, only a very limited number of common frequency ranges such as the 2.4 GHz ISM band can be used.

B) Cost Factor

As the price of the container itself is around 1500 US dollars [10], one might argue that the monitoring and tracking system must be much cheaper. However the price of a container when used for many trips is irrelevant compared to the shipment cost of around 4000 dollars on average (shipment cost depends upon type and weight of commodity and type of insurance) and the number of shipments. If the quality of transport can be monitored and guaranteed, insurance fees could be lowered, hence the proposed container monitoring and tracking system could pay off for the reduced fees alone. Nevertheless a first estimate indicates that a solution of several hundred US dollars, container should be feasible for a volume application. Apart from the initial cost, maintenance cost is the main concern of any sensor network deployment. The maintenance cost can be kept low if the need to replace batteries is minimized or avoided (by scavenging natural energy available in the form of vibrations and wind). If primary batteries are used a service interval of 5 or more years is acceptable as an inquiry by us has shown.

C) Topology

Topology selection is a critical issue in container tracking and monitoring application. The natural choices available for wireless sensor networks are star and mesh topologies. Star topology imply that each IM must be able to communicate with container wide CM. This would mean that the IM's comparatively far away from the CM will have to increase the transmission power to overcome the signal attenuation and losses but at the same time would drain more energy (more transmission power, more energy drainage) but having point to point connection will result in less transmissions and hence lower chances of collisions. In contrast to star topology, mesh topology, where each IM within a container would rely on neighbor IM to rely its message, so the transmission power can be kept low and hence energy can be saved. But mesh networking has its own disadvantages, for example IM's near the CM would always be used for transferring data and hence drain all its energy sooner than the other IMs in the container and result in an unconnected graph (Fig. 5).

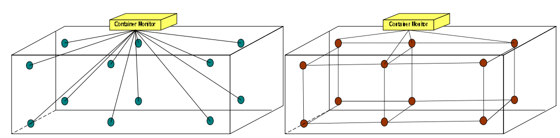

Figure 5: Star and Mesh topology

There are container ships which can carry around 14500 containers [12]. In trains, the numbers of containers is much less and the environmental conditions are better than in ships. In container ships, the huge number of containers would result in more complexity as compared to ships but the basic principal of tracking and monitoring of containers remains the same. The physical arrangement of IMs and CMs in ships can play an important role because of the effects like attenuation and multi path propagation [21].

D) Retrieval of Contextual Information

In-depth investigation would be required to retrieve the contextual information. For instance, how can one figure out that a particular item has been damaged during transportation. Thought the acceleration and vibration sensors would help in this context but the resistance to these parameters varies from item to item. So for this purpose extensive knowledge of

Ambient Intelligence needs to be applied to overcome the challenge.

E) Routing and MAC schemes

For the specified application, the requirements which influences the routing and MAC schemes within a container includes, 1) small number of nodes, 2) no scalability, no interference from outside because of thick metallic box, and 4) infrequent topology changes (depending on container being full or empty). For the network of CMs, it needs to be scalable, and would additionally require sink selection algorithm (SSA) to work on the top of our proposed schemes. SSA is important, because it would enable the CMs to access global communication via PM (unlimited energy device) and hence save energy for bad times (when no PM is available and it has to communicate directly with GPS at cost of more energy consumption) . It is required to have energy efficient routing and MAC schemes to have an extended network life time.

Different routing strategies including DSDV [22] based on maintaining and generating routing table updates, AODV [23] based on acquiring routes on demand at the cost of route acquisition delay, EAR [24], based on selecting minimum energy path in a probabilistic manner and EADV [25] based on energy aware routing are proposed. In the current situation, EADV satisfies the requirements in a better way. As EADV depends on information of neighbor nodes only, it can very easily tackle scalability and topology issues. Secondly, as the change of topology is infrequent, EADV also initiates the network (re)initialization infrequently to conserve energy. Most importantly, it is energy aware routing protocol and is best suited for low power solution.

Previous work on energy aware MAC scheme comprise of many proposals. As we will have small number of nodes in a container and hence low traffic, we only consider energy efficient random access MAC schemes.

Berkeley-MAC [26] uses a tone to wakeup sleeping neighbors, and uses long preamble sampling at the cost of introducing additional delay. WiseMac [27] is also based on preamble sampling of the medium. It learns the sampling schedule of the nodes and accesses the medium at the right time. The protocol is adaptive to high and low data traffic loads. CSMA-MPS [28] "*attempts to improve energy and latency over B-MAC and WiseMAC*" [29] and is well suited to meet the demands of low power applications.

To further enhance the energy consumption and improve quality of service, dynamic network software which adapts itself to the current network conditions and application requirements and benefiting from opportunistic exploitation is required. To attain it, we intend to introduce an application management plane which controls the duty cycle and other parameters of EADV and CSMA-MPS which we plan to integrate in our solution as routing and MAC schemes.

F) Energy

Energy efficiency is one of the main concerns. Besides energy efficient communication schemes and sensors, other techniques are also required to conserve energy.

Several state-of-the-art sensors and low power microprocessors have been analyzed in order to identify an efficient system configuration and operating modes in the states where the container is stationary (passive tracking) and when the container is moved (active tracking).

Based on some simulations, the Container Monitor is estimated to consume about 200µW (140mWh monthly) average power in the passive tracking state with GSM sending daily update messages and GPS deactivated. In this state the node must be able to detect and track any acceleration with very short latencies if a certain threshold is met. Energy scavenging systems able to extract energy during cargo transport (wind, vibrations…) would need to produce some excess of energy to overcome the possible long time a container may stand still. During active tracking state were data is logged on a continuous basis (acceleration in 3-axis at 20-50 Hz), the average power consumption is much higher and estimated to be about 90-150mW. This includes storing all relevant data on a mass storage device such as a flash memory. Figures 6 show some typical power consumption profile for Container Monitor.

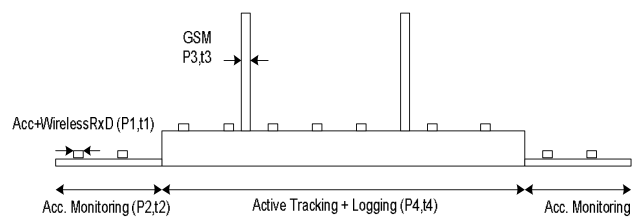

Figure 6: Central Unit: typical power consumption profile

P1,t1: WSN communication and Acc. Monitoring: t1: o.o. (order of) ms, P1: o.o. 10-50mW

P2,t2: Acc. Monitoring only, t2: o.o. days, P2: o.o. 10-100µW

P3,t3: GSM Network login and Communication: t3 o.o seconds, P3: order of 250mW average

P4,t4: Active Tracking and Logging: t4: o.o. hours, P4 o.o. 100mW.

Some conservative numbers from Rail-Cargo Austria indicate that typically leasing containers may travel 100000Km on railways yearly, which is about 1300h or (117Wh-195Wh). This is the equivalent of a fairly large 20Ah Lithium Battery which is discharged within 4-6 month. However some containers owned by companies may have completely other figures. These power figures indicate that the service interval needs to be minimized by some means. Energy scavenging is therefore a compulsory feature of such a system. The problem of extracting and converting the available energy from the environment is a challenge yet to be solved.

G) *Security*

Because of limited resources, security requirements in wireless sensor networks are more challenging than conventional networks. Security for wireless sensor networks entails key establishment and trust setup, secrecy and authentication, privacy, secure routing, intrusion, and secure data aggregation [30]. A secure container tracking and monitoring application is of utmost important as malicious data can disrupt the trading at the port. For instance, let's assume that some one has hacked the application and is reporting false data that the containers contain explosives very dangerous for the port. In this case, operations on the port may be stopped, and unnecessary effort would be made to cross check the results reported by the application.

VI. CONCLUSION

This paper proposed a system architecture for container tracking applications and discussed the main challenges yet to be solved. At the Institute of Computer Technology, WCMS (Wireless Cargo Monitoring System) research project is initiated in 2007 to tackle these issues by building a prototype network and by evaluating it on cargo trains together with other partners from academia and industry. We are well aware that this application entails many business processes and poises a lot of technical and non technical challenges. Like, in container trade, exchange of a physical container is a normal practice. What would happen if a "smart container" has to be exchanged with a normal container? What if owner of shipment argues that all the cost damage is paid by insurance company? We will have to answer many such questions when we progress towards the realization of the concept.

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