SCN: An Efficient Wireless Sensor Network Based Communication Scheme for Stacked Containers

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Abstract

Traditionally it's impossible to monitor the freight's status inside a container which is made of steel and makes data transmission by radio impossible, let alone the wired communication solutions. As container transportation is the prevailing method for international cargos, a feasible way to transmit status of the monitored cargo out of the stacked containers is very important, especially for ones with special requirements such as dangerous goods. This paper proposes a scheme to construct a communication network for stacked containers by deploying communicating nodes on the container's surface to form a customized wireless sensor network. An effective routing algorithm is also proposed to exploit the characteristic of the network which is composed of smart containers. Simulation results show that the proposed interconnecting scheme makes an effective communicating infrastructure for upper layer container management services.

Keywords: *Smart Container; Container Network; Wireless Sensor Network; Routing*

1. Introduction and Related Work

With the advent of economic globalization, more than 200,000 standard containers have been used in the global trade nowadays, and they have born 90% of world's trade transportation. Nevertheless, the attention on the international container transport security keeps rising constantly as more and more security issues were reported. During the transportation process, container is a steel-made opaque black box and usually encircled by other containers. Outside world cannot know whether its internal cargo is safe as there is no way to send data out from the piled container stacks. A lot of new worldwide regulations and initiatives had been introduced regarding to the container safety [1], but there is still no effective measure to monitor the status inside contains efficiently.

In the field of container tracking and positioning, RFID-based electronic tagging system has been used [4]. Comparing with other solutions, container positioning and tracking system which are based on RFID is simple to deploy, and convenient to conduct positioning, but still has many shortcomings. For instance, tags can't compose a network because installing electronic tags on containers can only passively read and these tags cannot communicate with each others. Besides, RFID readers can only be deployed at a limited number of particular locations such as port gate etc.

Therefore, building a container positioning system based on wireless sensor network is a nature choice. The features such as flexible deployment, no infrastructure required, longer communication distance, and the real-time accurate positioning are all WSN's advantages [2, 3]. However, there are still two problems hinder the application of WSN to container monitoring and tracking. The first one is communication shadow which is brought by the stacked steel made containers. And the second one is energy consumption issues which are introduced by traditional WSN communication methods.

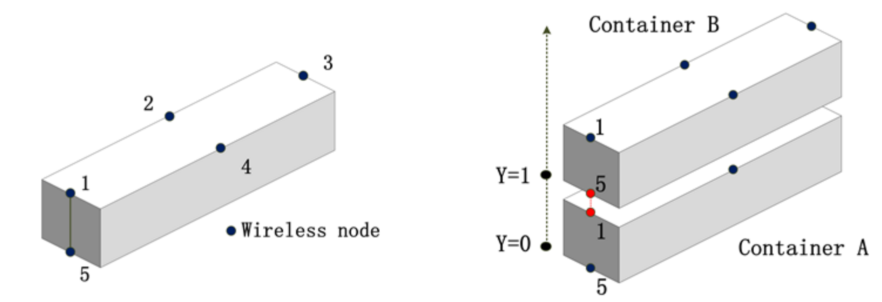
Fu and Zhou [8] proposed a WSN and wireless data transmission technology based intelligent monitoring and tracking system for the refrigerator containers, Bai and Zhang also proposed similar solution [5]. They put forward the idea of establishing a wireless sensor networks to conduct the inner container monitoring, and then transmitting data to a designated server through GPRS network. Zhang Yingjun, *et al.*, also proposed similar ideas to solve the problem of tracking dangerous goods [7]. However, besides data transmission through the GPRS network, these schemes still didn't consider how to solve radio shadow issue which is identical to the RFID-based systems. Su Jin Kim et al further proposed a way to combine RFID and WSN technology to monitor the illegal openings of container; however this scheme only realized the communication among the containers that are stacked one by one vertically, thus the overall container data still cannot be effectively transmitted [6].

Unlike the aforementioned work, in this paper, we propose a effective scheme to interconnect smart containers and make themselves the communicating infrastructure for upper layer applications. The rest of this paper has been organized as follows. In Section 2, we present the container interconnection scheme SCN (Smart Container Network). In Section 3, we present the experiments results. Concluding remarks are included in Section 4.

2. Communication Scheme for the Stacked Containers

2.1. Interconnecting the Stacked Containers

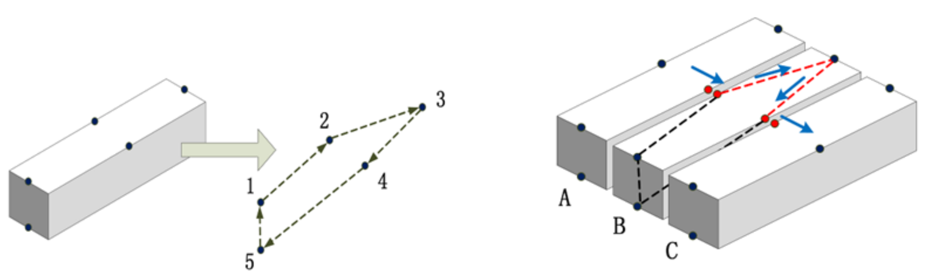
2.1.1. Communication between neighboring containers: As shown in Figure 1, each container will be equipped with five wireless communicating nodes which are built with low energy consumption hardware. All these five wireless nodes have the same container identify number (Container ID) and a deployment position number (Position ID). The former is used to get the exact position of the unique host container. The latter denotes the position of these nodes when mounted on the container's inside wall by hard wiring. The communication range of all these nodes is limited to a quite small distance (*e.g.*, 0.8 meter), so that only when a container is close to another one, there can be a connection between them being set up. After one wireless node sets up connection with another one, they will both know that there exists another container and then collaborate to establish communicating link, thus form a small smart container network cluster. In addition, according to the locations of wireless nodes on the containers that having link to each other, relative coordinates between the two containers will be assigned. As shown in Figure 1, if node 1 of container A is connected to the node 5 of container B, then after establishing a connection, we can determine that the container B is stacked on the top of the container A, thus the relative coordinates of these two containers can be obtained. If node 5 of the container A has not established a connection with any other nodes, it can be inferred that the container A is at bottom layer, thus the absolute coordinates of the containers can be obtained accordingly. Similarly, as long as there is a new incoming container being stacked onto the existing container network, the container network cluster will grow automatically and the addressing system will refresh all nodes' coordinates and all containers' relative positions.



A). Wireless node deployment diagram B). Connection of wireless nodes

Figure 1. Communication between Two Neighboring Containers

2.1.2. Communication inside a container: As shown in Figure 2, each container will be equipped with 5 wireless nodes. Cables such as USB cable can be used to form a ring of nodes in the interior wall side of the container. Data transmission among the nodes takes a sequential ring communication way. Thus the routing table is static, and the packet routing path would be from node 1, to node 2, until to node 5. If a node receives data packet, it should first use dimensional order routing (DOR) to determine the next hop container, so that it can obtain the Position ID of the destination node in this inner container transmission. Then, it compares its own Position ID with Position ID of this inner container destination node. If not, then it transmits the packet in a clockwise manner. This transmission will keep going on until the inner container destination node is reached. Then the data packet is transfer to the exterior side to be sent to node of next hop container. For instance, as shown in Figure 2(B), container A needs to send a packet to container C. Packets is sent from node 4 of container A to the node 2 of container B, then it enters into the box of container B. Node 2 of container B uses DOR to find the next hop is the container C on the right side, therefore the inner container destination node is node 4. Thus, the packet takes a clockwise loop through node 3, and reaches node 4. Once node 4 receives the packet, it uses the external wireless link to send the packet to node 2 of container C. The routing decision function for intra-container communication is defined as formula 1, where R_{intra} is routing decision function, n_i is a node, *des* is the target node which is determined at the time when inter-container routing decision is made.



A). Ring route inside a container B). Packet transportation between 2 containers

Figure 2. Communication Path Inside a Container

$$R_{inrtra}(n_i) = \begin{cases} n_{(i+1)}\%5 & if\,(n_i \neq des) \\ n_i & if\,(n_i = des) \end{cases} \quad (1)$$

2.2. The Data Routing Method

In order to make the container network feasible in real world applications, low-energy consumption, low-latency communicating method has to be designed for this wireless sensor network with 3D mesh topology. Traditional routing methods such as AODV and DSR etc do not seem to be good choice here as they are energy demanding and require unnecessary communication overhead due to regular broadcasting or route discovery. In this article, we proposed a novel simple dimensional ordered routing method, SDOR. The purpose of this algorithm is two folded. One is to explore the characteristics of the stacked containers and then find the shortest route that can delivery packet from a container to the target node, the other is to save energy of all the communication nodes in the whole network. We will introduce them respectively in the follows. As five wireless nodes are deployed in each container, they all have identical Container ID. In addition, they are interconnected with hard wires. Therefore, to simply the routing algorithm description, they can be abstracted as one node set. Each node set maintains a state table of its adjacent node position as defined in Figure 3(A):

```
Struct LocationStatusTable {
  bool UpLinked;
  bool DownLinked;
  bool LeftLinked;
  bool RightLinked;
  bool BehindLinked;
  bool FrontLinked;
   ……
}
```

(A). Data structure representing a node's connection status

$$R_{inter}(N_{xyz}) = \begin{cases} N_{(x-1)yz} & if\ N_{xyz}.LeftLinked \wedge D_i x < N_{xyz} x \\ N_{x(y-1)z} & elseif\ N_{xyz}.FrontLinked \wedge D_i y < N_{xyz} y \\ N_{xy(z-1)} & if\ N_{xyz}.DownLinked \wedge D_i z < N_{xyz} z \\ N_{(x+1)yz} & if\ N_{xyz}.RightLinked \wedge D_i x < N_{xyz} x \\ N_{x(y+1)z} & elseif\ N_{xyz}.BehindLinked \wedge D_i y < N_{xyz} y \\ N_{xy(z+1)} & elseif\ N_{xyz}.UpLinked \wedge D_i z < N_{xyz} z \end{cases}$$

(B). SDOR routing decision function

Figure 3. Inter-container Routing Decision Function for SCN

SDOR relies on querying the status table of adjacent node to determine next hop node, the algorithm definition is shown in Figure 3(B), where R is routing function, N_i is node-set, S_i is source node set, D_i is target node set, x is the coordinate at x-axis, y is the coordinate at y-axis, and z is the coordinates at z-axis. As defined by the formula, SDOR routes the packet sent from a container by following the direction sequence of x-axis, y-axis and then z-axis, until it reaches the destination node. The destination container is assigned with the coordinate (0,0,0), and behaves as the gateway that forwards data to the existing communication infrastructure such as WIFI network. When the existing route is broken, as shown in Figure 4(B), the routing decision is still made according to the dimensional order. When packet cannot be

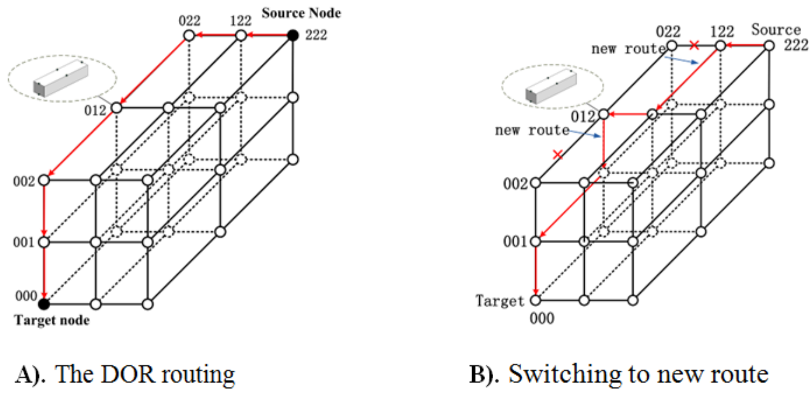


Figure 4. Packets Routing in SCN

transmitted on x-axis, then the next hop will be the node on y-axis; and when packet cannot be transmitted on y-axis, then the next hop will be the node on z-axis. Due to the way that the containers are stacking, z-axis is the vertical direction and much less unlikely to be disconnected. If connections at the 3 dimensions are all broken, then a new container cluster will be formed and the target node for the new cluster will be elected to forward the packets to existing communication infrastructure. Our simulation results shown that the dimensional ordered routing algorithm presented above has a good performance in terms of average energy consumption and average packet delay. However, the energy consumption at bottleneck link nodes is much higher than other nodes. We define the bottleneck link nodes as the nodes that form the communicating route of the packets at one plane. The network can get collapsed when the bottleneck link nodes run out of energy much quicker than others. To avoid this situation, SDOR conducts a dimensionally scan to balance the usage of all the nodes in network. That is, based on the dimensional order algorithm described above, SDOR sets an energy consumption threshold at each bottleneck link node, say 10% of initial energy. Once energy consumption of any node on the bottleneck link exceeds 10%, this node will initiate a broadcast in the whole network which announces that the bottleneck link is shifted one unit toward a specified direction. Then when source nodes send packet after knowing this announcement, the route will be a new one. This process is shown in Figure 5. We call this process as energy consumption rotation. The rotation is conducted on a specified plane, thus

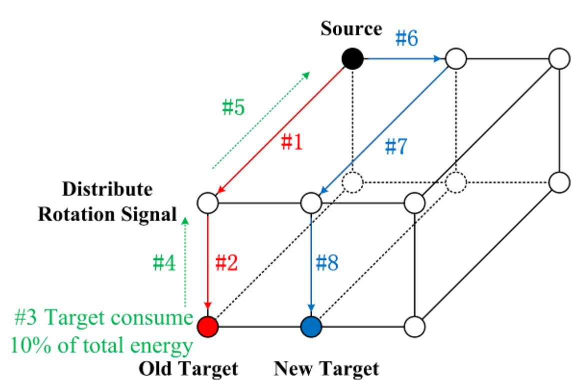


Figure 5. Signal for Route Rotation

the energy consumption of every link on this plane is in a cyclic way. Therefore, the energy consumption on one dimension is distributed to two dimensions, which makes the entire network survive longer. The complete SDOR algorithm is presented as follows.

```
……
if (Energy consumed by ThreshHold)
        Change(Target)
if (output)
if (Left Linked) AND (x > Target.x)
        Next Node = (x-1)yz
else if (Front Linked) AND (y > Target.y)
        Next Node = x(y-1)z
else if (Down Linked) AND (z > Target.z)
        Next Node = xy(z-1)
else
        Change(Target)
else
if (Right Linked) AND (x < Target.x)
        Next Node = (x+1)yz
else if (Behind Linked) AND (y < Target.y)
        Next Node = x(y+1)z
else if (Up Linked) AND (z < Target.z)
        Next Node = xy(z+1)
else
        Change(Target)
……
```

3. Simulation Results

3.1. Simulation Configurations and the Simulated Metrics

Simulations are carried out on a customized simulator which is built on an open source WSN simulator [9]. As mentioned before, we treat a smart container which is equipped with five communicating sub-nodes as one node in the mesh network. The simulation experiments were conducted on three dimensional mesh networks with various scales, such as 3*5*7 and 4*6*8 *etc.* Also, as described in Section 2, each node’s communication scope is assumed to be only able to overlapping with its neighbor nodes and the communication channel is duplex. In addition, to simply the simulation so we can concentrate on SCN’s performance, we also assume the communications take place in one container cluster. Since we assume there is no node that runs out of energy, the simulation results of DOR and SDOR will be identical.

Therefore, we assign the target node at (0,0,0) to simplify the simulation settings. Thus all packets' target is fixed as the node with coordinate (0,0,0). In the simulation experiments, every 0.5 second s a node is randomly picked to send a message to the target. Data packets sent in the network are in various sizes such as 250bit, 500bit and 1000bit *etc.* The initial energy for each node is set to be 1000 unit.

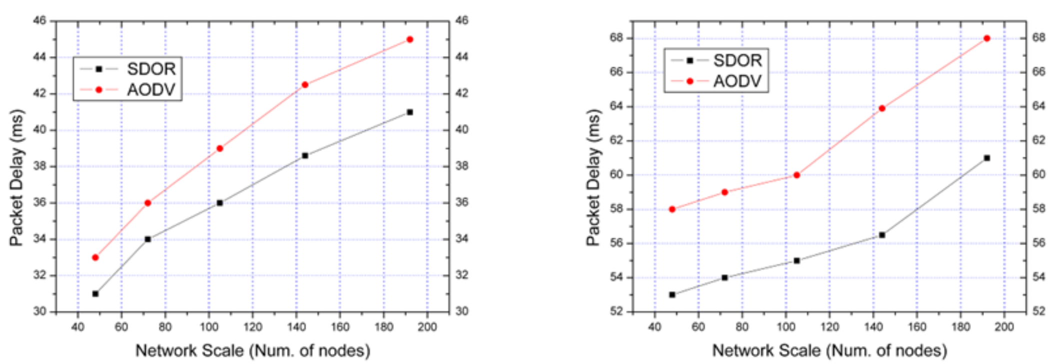
Other pertinent settings are as the follows. Sending one packet costs 1 unit energy; receiving one packet costs 1 unit; sleeping for a cycle costs 0.001 unit; and the transmission delay between two nodes are 10ms. When the target node receives the 100th packets, we record the remaining energy of all the nodes in the network. The metrics we examined in the experiments are average delay Delayavg and energy consumption *EC* which are defined as follows:

$$Delay_{avg} = \sum_{i=0}^{n-1} Delay_i \Big/ Num_{total}, \quad \text{where } Delay_i = T_{recv_i} - T_{send_i} \tag{2}$$

$$EC = \sum \left(E_{totalInit} - E_{totalFin} \right) \tag{3}$$

3.2. Simulation Results

As AODV is a widely used WSN routing method [10], we compare SDOR with it to evaluate performance of SDOR. The performance comparison results in terms of average packets delay and cumulated energy consumption is shown in Figure 6 and Figure 7 respectively. As described previously, SDOR is customized to better exploit the characteristics of smart container network, such as the regular cluster topology which is three dimensional mesh network, and infrequently cluster reforming. Unnecessary communications such as cluster head election messages are avoided. Thus we can see that SDOR is not only better than AODV in terms of energy consumption, but also slightly has lower message delay.



A). Data obtained with packet size of 250 bit

B). Data obtained packet size of 500 bit

Figure 6. SDOR v.s AODV on Average Message Delay

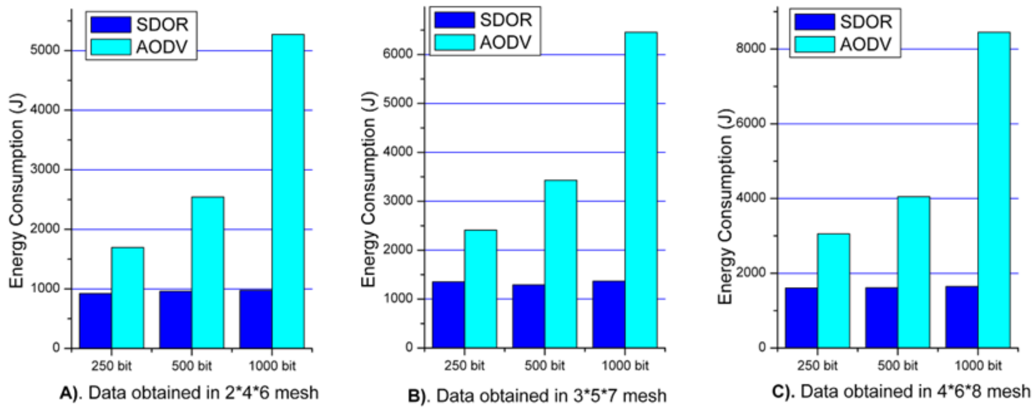


Figure 7. SDOR v.s AODV on Energy Consumption

4. Conclusions and Future Work

This paper proposes a novel communication scheme SCN to form a special three dimensional network which is composed of smart containers that are built on wireless sensor network. A customized routing algorithm SDOR is also proposed to exploit the characteristics container network. Simulation results shows that the proposed networking scheme can make a solid communicating infrastructure for upper layer container monitoring services.

In the future we'll keep on researching the clustering algorithm for container network, as well as how to implement the scheme into real application which can comprise of heterogeneous sensors and be able to continuously monitor internal status of the steel made containers.

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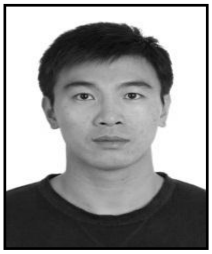

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