A Low Cost Approach to Large Smart Shelf Setups

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***Abstract*—Recent years showed a growing interest in the use of RFID technology in applications like distribution and storage of goods, supply chain and inventory. This paper analyses the current smart shelf solutions and presents the experience of developing an automatic reading system for smart shelves. The proposed system addresses the problem of reading RFID tags from items placed on multiple shelves. It allows the use of standard low cost readers and tags and uses a single antenna that can be positioned in specific locations at repeatable positions. The system proposes an alternative to the approaches with multiple antennas placed in fixed position inside the shelf or around the shelves, offering a lower cost solution by means of dedicated electromechanical devices able to carry the antenna and the reader to the locations of interest along a rail system. Moreover, the antenna position can be controlled for three axis of movement allowing for extra flexibility and complete coverage of the shelves. The proposed setup is a fully wireless one. It contains a standard reader, electromechanical positioning actuators and wireless communication and control hardware offering power from integrated batteries.**

***Index Terms*—Antenna radiation pattern, Inventory management, Radiofrequency identification, RFID tag, Microcontroller**

I. INTRODUCTION

In the last five years many organizations (big retailers, industrial companies, defence organizations) were testing and deploying radio frequency identification (RFID) technology in their supply chains.

The debate around the introduction of RFID technology has raised many important questions partly due to the very broad range of envisaged applications ([4], [5], [9], [11], [12], [22], [35], [39], [41], [46]). Main issues are related to cost effectiveness, reliability, robustness, security. For the field of applications discussed in this paper (distribution and storage of goods, supply chain, inventory) the main question is : "Will introduction of RFID result in substantial gains in efficiency and effectiveness of logistics processes, or it is this mere providing more than marginal benefits?". As the technologies used are becoming more mature, the cost of the hardware lowers and the aspects of data reading/writing/transmitting at different levels of the infrastructure are becoming more and more standardized, this question receives a positive answer.

Both active tags and passive tags are showing many potential advantages of RFID technology in the supply chain ([1], [2], [3], [21], [34], [37]). Passive tags do not contain any power source. They are powered by the inductive power received from the tag reader and their range of transmission can be relatively short. The active tags contain a power source and are capable to transmit over relatively long ranges.

Several advantages of the RFID technology for the distribution and storage of goods are summarized in [38]:

- the potential to automate the distribution of goods in the supply chain between manufacturing plants, warehouses, and retail stores of different organizations

-the ability to provide up-to-the-minute information on sales of items, and thus an accurate picture of the inventory levels

-reduction in inventory levels, thus causing a reduction in inventory costs

-complete identification of all items, thus cutting down losses from lost/misplaced inventory items.

II. RFID FOR DISTRIBUTION AND STORAGE OF GOODS

The introduction of RFID in the supply chains is a process whose costs and benefits should be carefully considered ([38], [43], [14]). There is a typical case of updating an working system (mainly barcode based) with a new technology that hast to integrate with the existing established IT infrastructure. The transition of an item along the supply chain at the item level, case level or pallet level from the manufacturer to the final customer can be completely handled on an RFID base as indicated in Fig. 1.

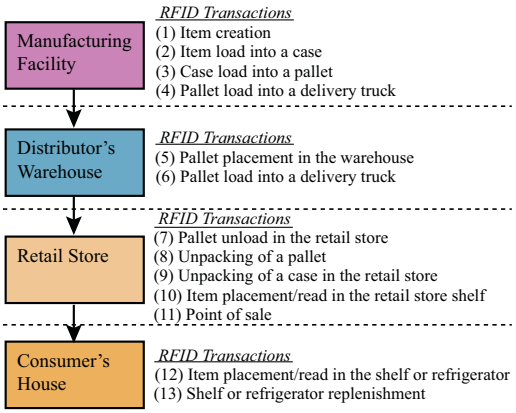

Figure 1 Transition of an item along the supply chain (after [38].)

For the scope of this paper is particularly relevant how the RFID systems working at shelf level can be integrated at the store level an how the information provided by them is further processed and interpreted in the software platforms at an enterprise level. Relevant architectures for the example of retail business are indicated in Fig.2 and 3.

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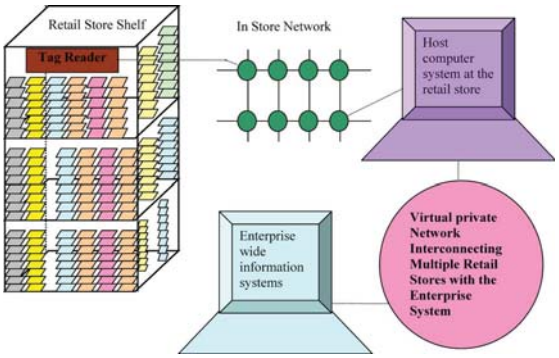

Figure 2 RFID infrastructure in a retail store (after [38])

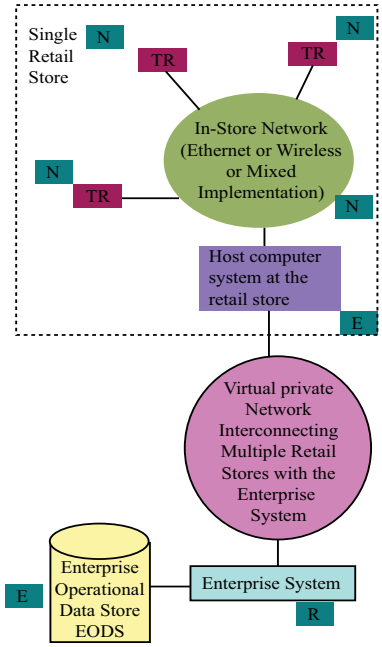

Figure 3. Interconnecting infrastructure in a retail store (after [38])

III. Smart Shelves Solutions

Several different solutions are actually proposed for RFID based smart shelves. Some of these are presented on the basis on the information available in literature (articles, presentations or company product brochures) in order to compare the solution proposed in this article with other implementations. Before going into the details of each solution is worthwhile to consider some criteria which ideally each smart shelf solution should satisfy:

-ensure that the shelf antenna reading capability is confined to the volume of interest and does not extend to other shelves;

- existing standard passive UHF tags (the cheapest but with shorter range) are compatible with the reading solution;

- the solution should cope with different shelf sizes and shelf types

-the overall system (antennas, readers, associated communication and control electronics) should be cost effective

- the solution should be scalable in order to accommodate for setups with large number of shelves.

It should be mentioned that the specific properties of the products stored on the shelves are influencing the chosen smart shelf solution leading sometimes to dedicated systems, specifically implemented for a certain type of products. The main aspects that deserve designer's consideration are:

- the type of the material of containers holding the products (paper, cardboard , plastic, glass, metal, wood, etc.)
- the type and the thickness of the materials from which the shelves are made
- the size and geometry of the items on the shelf.

These aspects are all relevant when the problem of the coverage of the antenna system ([13], [16], [17], [25]-[27]) or the problem of tags reading are considered: metal items to which tags are attached and thick metal shelves metal bring many technical challenges ([7], [8], [28], [30], [47]). Substantial research effort is dedicate to improvements in antenna and reader designs ([15], [32], [33], [36], [40], [42], [45]). There is a matter of cost efficiency which also rises in this context: can the actual setups of shelves currently found in storage rooms be transformed into a smart shelf system or the whole infrastructure should be replaced (new special shelves) in order to have a fully working system?

The approach described in section IV is motivated by this question.

One of the mostly used approach to the problem of reading tags attached to items placed on shelves is to use multiple antennas in order to "cover" shelves space ([28], [29], [31], [48]).

The systems described in the literature are usually accomplishing this through the usage of multiplexers (see Fig. 4 and 5).

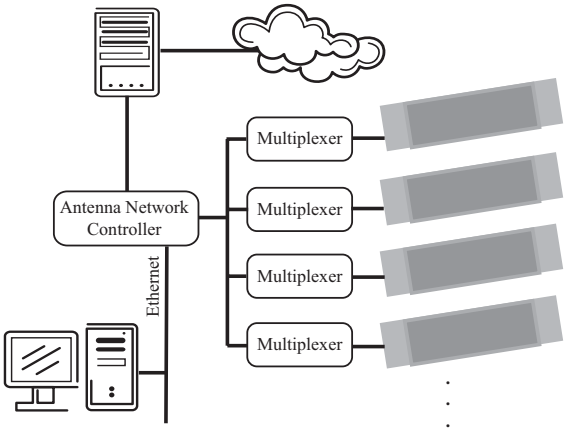

Figure 4. Antenna network controller interfacing multiple antennas (after [48])

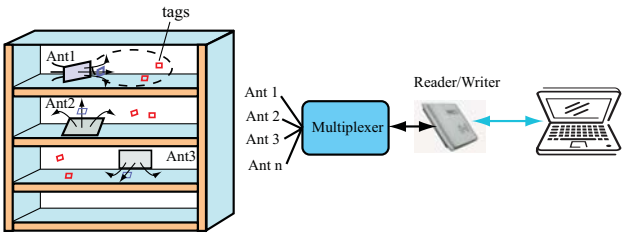

Figure 5. Simplest connection of multiple antennas through an multiplexer (after [29]).

The proper placement of these antennas can help in getting a wider space covered and avoiding in such way false negative queries when trying to look for an item which is not "visible" will infer that it is missing from the shelf.

The setups suggested in [29] and in [31] and represented

in Fig.5 and Fig.6 are trying to maximize the reading space of the antenna system by placing the antennas in a position that helps in complementing each other for various tags position and angles relative to the antenna plane.

A regularly placement of the tags, like in the case of tags attached to books [29] may provide a particular context for which a predefined distribution of the magnetic field is desirable as indicated in Fig.7.

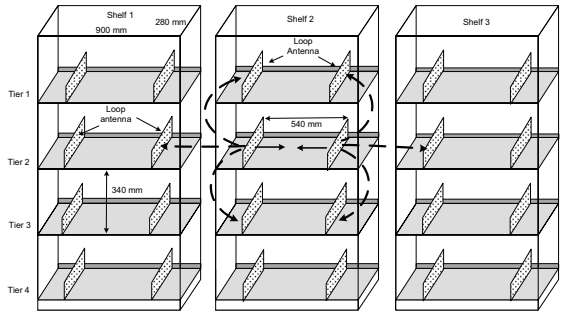

Figure 6. Interference between the adjacent tiers may degrade the system detection/localization accuracy

The placement of multiple antennas not only maximizes the reading capabilities but also introduces new issues: in a situation like the one in Fig.6 it is possible to read from a neighbouring shelf, placed below, above or next to the shelf for which a specific antenna was intended.

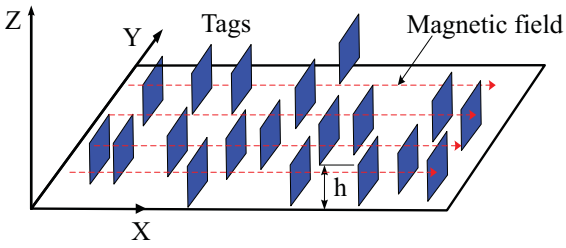

Figure 7. Regularly placed tags

An alternative to the usage of several antennas is indicated in [44] and represented in Fig. 8. It starts from the idea of creating the required coverage through a multiple loop antenna whose geometry is appropriate for being incorporated in the shelf. In this way a cost reduction is achieved but this setup will not work well for metal shelves.

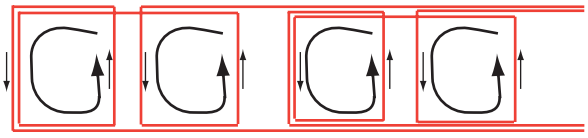

Figure 8. Special antenna configuration

A smarter approach is indicated in [24]. The representations from Fig. 9-11 are suggesting the idea behind this antenna setup: if pairs of antennas having horizontal and vertical polarizations are used in such a way that their coverage patters are complementing each other, than is no longer needed to attach an antenna to each shelf.

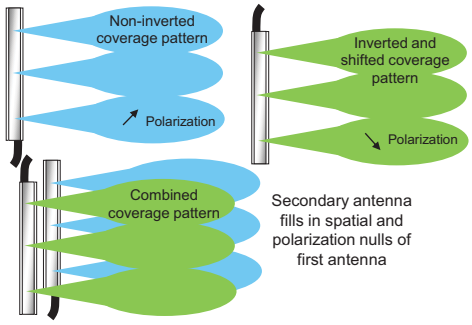

Figure 9. Complementary radiation patterns (after [24])

There is possible to obtain in this way a very good coverage for a volume in which multiple shelves are confined with a reduced number of such special antennas.

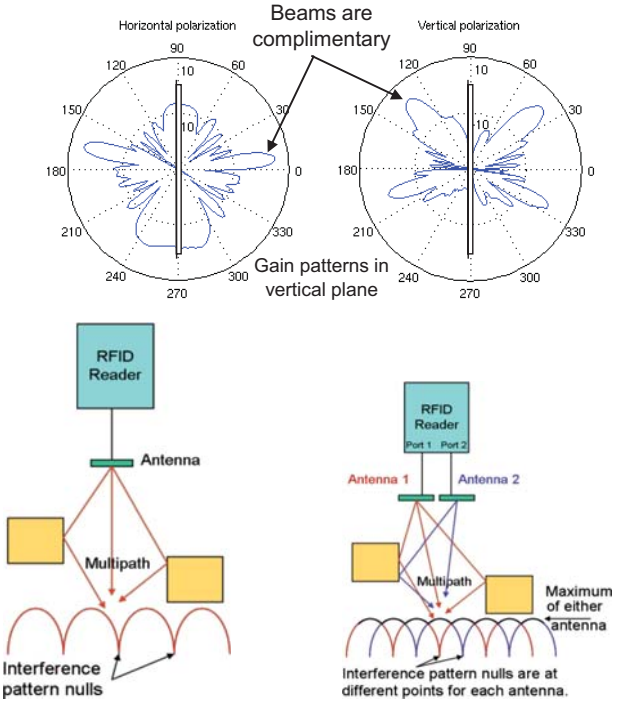

Figure 10. Setup for overcoming fading with antennas in mounted in pairs (after [24])

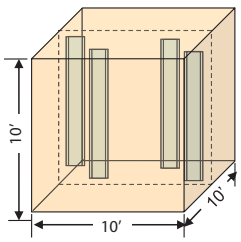

Figure 11. Setup with four centre mounted antennas (after [24])

The "granularity" of the reading process is degraded in a setup as the one of Fig. 11: the exact placement of the object on the shelf is an indication difficult to obtain.

A combined solution giving an excellent localization of the tags indicated in [6] is represented in Fig.12. Through a combined usage of a small antennas array and optical switches the localization is achieved: a solution particularly fitted to special shelves holding items with regular geometry.

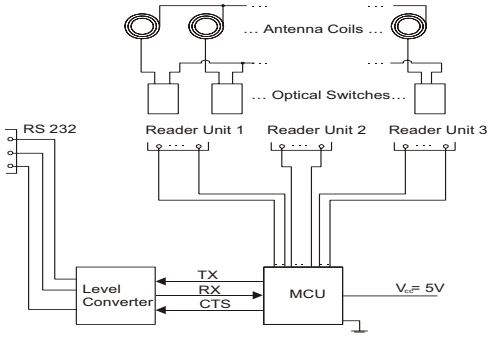

Figure 12 Schematic of a Smart Shelf able to report the basic actions *take*, *return* and *remove* to a backend system (after [6])

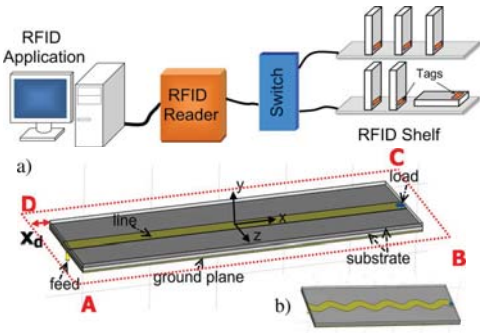

Figure. 13 Smart shelf configuration using embedded leaking microstrip transmission line with extended ground plane (after [19])

An interesting approach, suitable both for static items (on a shelf) and mobile items (on a conveyor belt) is indicated in [19] and [20]. It is based on the usage of special antennas built as meandered strips in order to accommodate for all possible angles of the tag plane relative to the antenna plane (see Fig.13).

IV. Implementation of The Proposed Smart Shelf System

The proposed system addresses the problem of reading information from tags distributed across a large number of shelves.

It starts from few basic design constrains and remarks:

the solution must be usable with existing shelf infrastructures found in storage facilities

low cost "classic" antenna should be usable

the overall cost of the system hardware should be reduced as much as possible

the much praised speed of the RFID based inventory system is not the most important factor for many applications: an update rate of tens of minutes or of few hours is in many cases acceptable since having an inventory updated every minute is simply not necessary.

The idea of the system is to use a mobile unit mounted on a carriage **C** which is moved along a rail **R** through the movement generated by an electric motor **M** as depicted in Fig. 14.

To the carriage **C** a unit consisting of a small form factor PC motherboard, three motor drivers, three stepper motors and an RFID reader is attached (see Fig. 15). The antenna connected to the reader is depicted in Fig.16 and the magnetic fields it generates in two planes are represented in Fig.17 and 18.

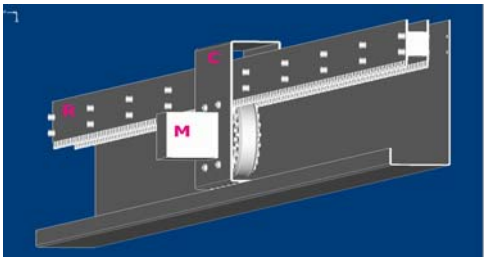

Figure 14. Rail system for mobile reader

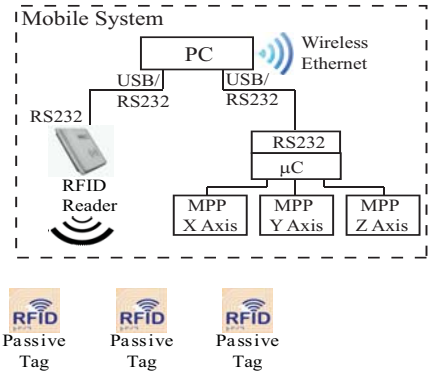

Figure 15. Architecture of the mobile unit

The whole mobile system is powered from the battery included in order to achieve an autonomous movement along the rail. While the first motor assures a translation along the rail (horizontal X axis) the second and the third one are mounted in order to move the antenna on the vertical axis Y and to allow the tilting of the antenna for a variable angle relative to the shelf horizontal plane.

The software running on the PC unit is responsible for the following tasks:

reading of a movement scenario which can be performed periodically at a programmable rate (Fig. 20)

parsing, sorting and interpreting of the data provided by the reader (a tag can be read more than one time with the antenna in different positions of the movement scenario) (Fig. 21)

wireless communication of the actual inventory information to the host system (see Fig. 19) via an Wireless Ethernet link.

A software application was also developed for an embedded module built around a low cost 8-bit microcontroller. Its main task is translating the serial messages received from the PC unit into appropriate command signals for the motor drives.

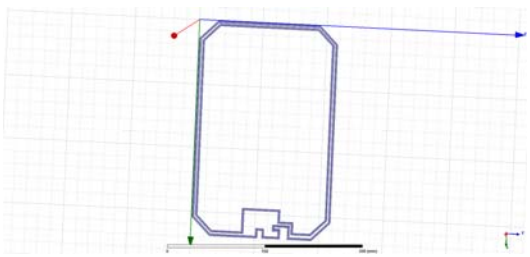

Figure 16. The single antenna configuration

While it is obvious that the proposed solution would not have the "reaction speed" of the setups with multiple fixed antennas, there are few facts that advocate for this mobile reader approach:

- the rail system can be extended as much as needed due to its mechanical setup (2m long rails are easily chained) allowing to cover large storage perimeters
- even for a considerably large number of shelves, a single standard antenna is used, no antenna switches and impedance matching units are necessary
- the overall cost of the system for a large number of shelves is considerably reduced compared to the costs of the other approaches described in section III
- the autonomy is gained using integrated batteries which are charged automatically in specific locations along the rail while the carriage is resting between two movement scenarios.

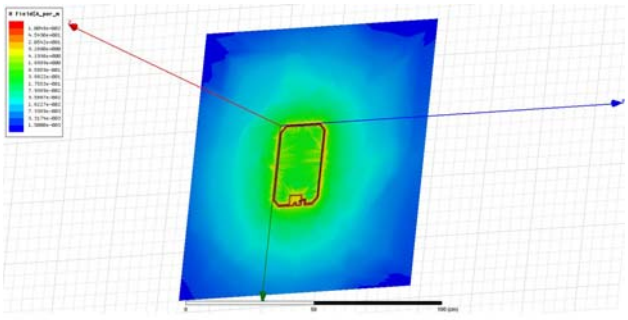

Figure 17. H field for a parallel plane

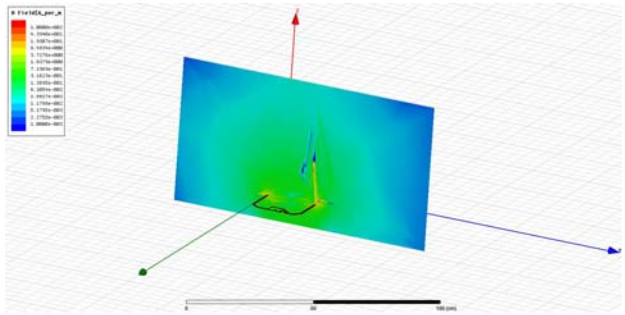

Figure 18. H field for a perpendicular plane

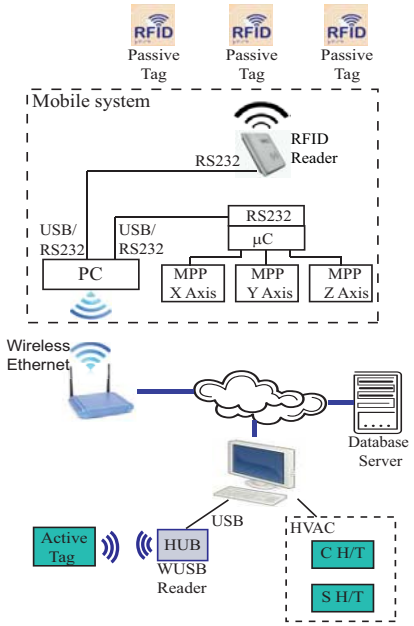

Figure. 19 Overall system architecture

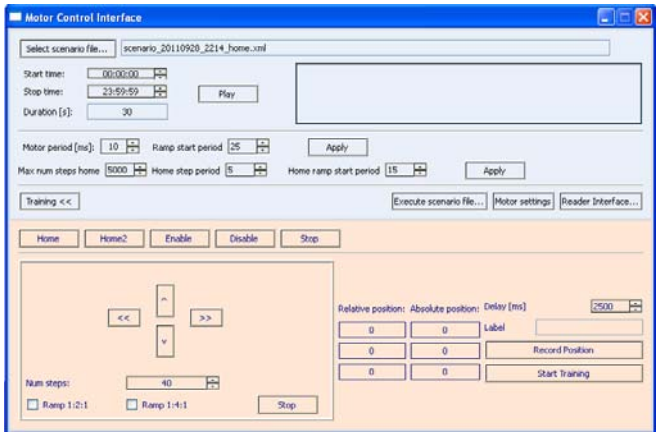

Figure 20. Movement control interface

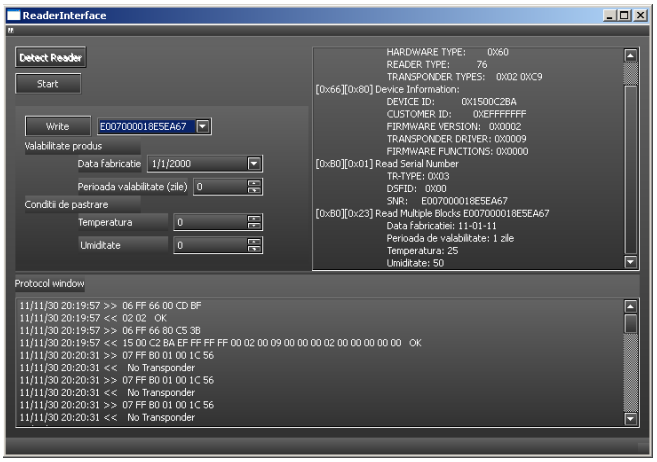

Figure 21. Reader control interface

V. Conclusions

An original low cost system has been implemented as a solution for large setups of shelves on which items with RFID tags are stored. It is suitable for a large store due to the scalability of the mechanical system proposed for moving the reader. The mobile unit is autonomous, with included processing facilities and with full wireless connection to the other components of the store management system.

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