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A Channel Selection Method to Increase Wireless Sensor Battery Life

A. FLAMMINI, E. SISINNI, D. MARIOLI, A. TARONI
Department of Electronics for Automation
University of Brescia
Via Branze 38, 25123 Brescia
ITALY

Abstract: - In most of wireless sensor networks a single externally-powered coordinator collects data from several battery-powered nodes using a simple star topology. This paper presents an innovative approach, based on an adaptive channel selection method, to reduce sensor power consumption in heavy RF-noise condition. While managing the network, the coordinator can scan the spectrum looking for free available channels; then the coordinator chooses a "backup channel" and communicates it to sensors. If a sensor looses contact with coordinator on the main channel the proposed method furnishes the "backup channel" for a faster reconnection. Despite a complexity and consumption increase of coordinator, sensor battery life can sensibly increase (more than twice). A simple real network, based on WirelessUSB™ technology by Cypress, has been developed to experimentally evaluate performance, especially as regard RF power measurement capability of low-cost 2.4GHz RF-transceivers.

Key-Words: - wireless sensor network, low-power system, power aware protocols, RSSI, RF power measurement

1 Introduction

Wireless sensor networks [1] are widely used in many applications (medical, home automation, and so on). In many practical cases the adopted topology is the star one, since it is very simple to be implemented in a low-cost smart sensor. For this reason, authors have focused their attention to this kind of networks. Typically coordinator is externally powered so it can be always in the "listening" state waiting for sensors data. Sensors mainly sleep, periodically wakeup and measures and transmit measurement data if a change or an event occurs or to keep alive connection with the master; then they wait for the master acknowledgment and turn-off. As regard existing and well-known technologies, IEEE802.11-based solutions [2] offer good performance, but high power dissipation impedes simple sensor applications. Bluetooth [3] reduces cost and current consumption, but it does not offer a true low-power mode. For all these reasons, several manufacturers have proposed their proprietary low-power technologies, as WirelessUSBTM (WUSB) [4] by Cypress or CC2500 by Chipcon. Recently an IEEE standard, formally known as IEEE802.15.4, has been approved regulating the physical and MAC layers and ZigBee™, the result of a manufacturers alliance, has been proposed as its higher stack levels extension [5]. It should be remembered that a standard approach offers well-known advantages in terms of interoperability and flexibility, but often implies higher costs and, particularly important in this kind of applications, higher power consumption due to longer frames. This difference may diverge during initial network creation phase, in which each sensor affiliates to a coordinator, or if communication between sensor and coordinator fails, due to other RF traffic sources, requiring a reconnection phase.

According to authors, transceivers of different technologies and manufacturers will soon reach similar performances in terms of current consumption and symbol rate, whereas sensor battery life will depend mainly by power sources and communication protocols [6]. A very difficult feature to be "a priori" estimated is the effect of interference with other RF power sources. Once a particular frequency channel has been selected to connect coordinator and sensors, that channel could be successively occupied by others wireless power sources: in this case protocols, according to their medium access schema, provide a suitable way to choose another channel and reconnect coordinator and sensors. This phase must be as short as possible because sensor continues to transmit and receive frames and its power dissipation reduces battery life of an unpredictable time. Our proposal is to decrease the probability of sensor reconnection, as shown in following sections.

2 The Proposed Solution

As already stated in the introduction, in traditional star networks the coordinator is usually connected to an external power source, while sensors are battery-powered. Battery life depends on the time the transceiver is active to transmit or receive information. If no interference occurs with other RF sources, this time can be simply "a priori" estimated; otherwise several retries or reconnection procedures could be necessary dramatically decreasing battery life. The proposed solution aim is to limit sensor power consumption during retry or reconnection phase, despite of a complexity increase of coordinator. In particular, the proposed coordinator must be able to scan all the available channels and measure RF activity while it listens for messages coming from its own sensors, as shown in Figure 1. In this way it is possible to maintain an updated energy map of RF activity within its area coverage and identify a suitable "backup channel" to simplify sensor reconnection. In fact, if a sensor looses contact with coordinator on the main channel, it soon tries on the backup channel avoiding more complex procedures.

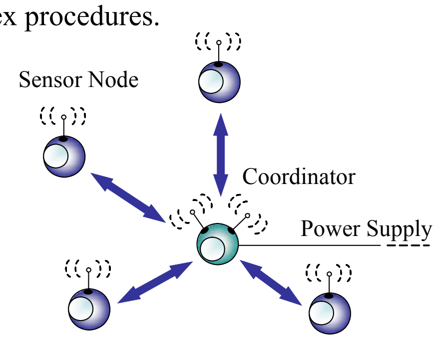

Fig.1. The proposed solution: an embedded instrument into the coordinator

As shown in the following sections, this approach can sensibly reduce sensor power consuming in a heavy noise environment, but the main problem is how the coordinator can dynamically choose the best backup channel.

The basic idea is to purposely dedicate an additional receiver to scan all the available channels within a fixed sub set; it must be stressed that such a device should be very simple, since it doesn't have to demodulate incoming signals, but only estimate RF-power. For this reason, it could be easily integrated in a transceiver without a sensible additional cost. However, in this work, authors have exploited the Received Signal Strength Indication (RSSI) feature furnished by most of nowadays commercial available transceivers. In fact, RSSI is typically used in "listen-before-talk" medium allocation schema.

Estimation bandwidth and observation time strictly depends on the adopted hardware, that must be carefully chosen. For instance, the already mentioned IEEE802.15.4 standard for low-rate personal area network furnishes the so called receiver Energy Detection (ED) over an observation time of 128μs. ED is a byte that is linearly related to received power in the range [-95…0]dBm. Also WUSB gives a sort of RSSI indication with programmable observation time. A RSSI readout provides a pure number from 0 to 31 that is related to power at the receiving antenna [-95…-40]dBm. In addition, if an isochronous master/slave topology is considered, a purely software solution can be adopted, utilizing the same transceiver for data transmission and channel occupancy estimation. Both approaches have been exploited in this paper.

In our proposal, the coordinator dynamically sorts channels according to their noise floor, partitioning available bandwidth in two (or more) groups. Initially, it selects the best channel (main channel) to transmit; in addition, another "good" channel (backup channel) is selected among other groups and coordinator sends it to devices in the acknowledge (ACK) packet every time a communication between sensor and coordinator occurs. If active channel suddenly becomes noisy, the coordinator changes it, choosing the backup channel. Similarly, every time devices loose the coordinator in the main channel, they search for it on the last received backup channel. If a link with the coordinator cannot be established, they will go in the sleep mode and wake up after a fixed time interval trying to reconnect again on both channels. This solution is rather independent from technology, and can be easily implemented on most of nowadays commercial available transceivers.

3 The Network Prototype

To evaluate performances a network prototype (real nodes, protocol) has been designed and realized; some simulation have been conducted supported by experimental results.

3.1 Technology choice

As regard technology choice, authors exploited a low-cost Cypress solution, but results can be easily extended to other 2.4GHz technologies.

Cypress Semiconductor offers the so called "Wireless USB Low Speed" solution to add the

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wireless capability to USB devices. Designed for wireless mouse, the CYWUSB6934 is a low-cost single-chip transceiver that exploits the DSSS modulation to reach a gross transfer rate of up to 62.5kbit/s. The medium allocation is based on a mixed architecture of TDMA/FDMA/CDMA techniques, probably its most interesting feature. The user is able to choose both the channel (among 78) and the spreading code, providing maximum flexibility. To establish a new star network the coordinator looks for a clear channel that becomes common to all its devices (sensors). When a device is turned on, it sends the so called "bind message" (7 bytes, ~ 0.9ms @ 62.5kbit/s) to search a coordinator in a fixed subset (typically 13) of channels. Four retries are performed for each channel and, considering a timeout of 10 ms related to "bind response" (11 bytes), this phase can take from ~2.5 ms to 570 ms @ 62.5kbit/s. After receiving network configuration parameters from coordinator, data transmission phase starts, in which sensor periodically wakes up, sends data (5 bytes + payload) and waits up to 10 ms for ACK response.

This approach, suggested by Cypress, works well in a low noise environment, but it can result in huge power dissipation in a crowded situation. In fact, if sensor does not receive ACK in time, it sends data again up to 4 times, then it selects next channel and repeats till all the 13 channels have been tried; finally, it sleeps and the whole binding procedure must be repeated when it wakes up. If active channel is noisy and coordinator changes channel, a sensor could take up to ~ 580 ms (payload = 4 bytes) to find coordinator plus eventually other 570 ms for binding procedure. A trade off between noise immunity and transfer rate can be obtained decreasing the transfer rate down to 15.625 kbps, since bigger spreading code (64 bits instead of 32 bits) are used. Obviously, transmission and receive time increase leading to a shorter battery life.

3.2 The designed protocol

In our proposal, an easier power saving procedure has been adopted. A simple isochronous topology has been considered, implementing a Time Division Multiple Access (TDMA) schema. Referring to Figure 2, each sensor sends data in its own time slot Si (i=1..M, being M the total number of sensors), while the D slot is reserved for acyclic communications or, as in this case, for diagnostic purposes such as energy map evaluation.

Data transmission and ACK packet are shown in Figure 3, where field length is expressed in byte. Fields CC and BC refer to currently used and backup channel, as further explained in the following. SINCRO is a special packet that allows node resynchronization; in this case, the field CC is replaced with the ticks number Tn ($-8 \le Tn \le 7$). Tn is related to time elapsed to the next wake up (Tcycle + Tn). The tick amount depends on the adopted hardware.

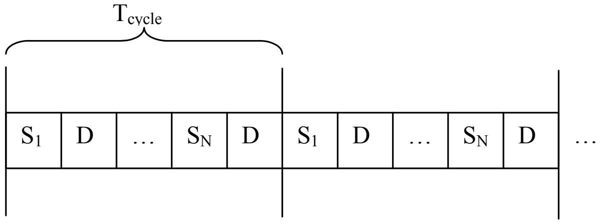

Fig. 2. TDMA multiplexing schema

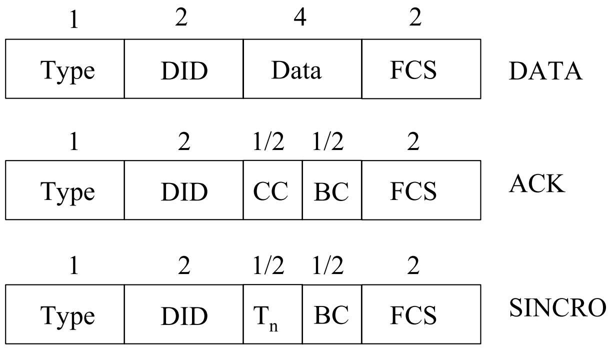

Fig. 3. Protocol datagrams; Type identifies the packet; DID is the device identifier, Tn allows for resynchronization and FCS is the Frame Check Sequency. Fields length in octet

Considering a useful payload of 4 bytes, sensor data transmission frame (DATA) is 9 bytes long. Coordinator answers with a 6 bytes long packet (ACK or SINCRO). A very small frame increase results if compared to reference WUSB network solution proposed by Cypress, which has a similar DATA packet but a 5 bytes ACK datagram.

Noise floor in the available band (2401-2479 MHz) is initially evaluated over an observation time in the order of 1s to choose start channel CC. Subsequently, a discrete number of channels is a-priori identified and each of them is evaluated by means of a so called "EN" parameter. EN is obtained by measuring RSSI over all set of available channels. How EN is computed depends on the adopted hardware, and it is described extensively in next section. All channels are divided into two groups G1, that contains CC, and G2; the clearest one within G2 is selected as a backup (BC). The BC value is updated each time a new minimum is reached and the actual value is greater than the average EN. Filters may be added to avoid

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continuous BC changes. Figure 4 shows the algorithm that regulates channel (Ch) selection.

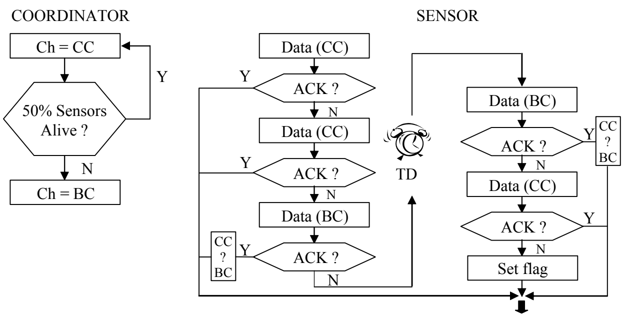

Fig. 4. Channel selection algorithm

If coordinator does not receive data from more than 50% of sensors, it means that CC channel is noisy, then BC channel becomes the active one (CC↔BC), starting from the next cycle. If failing condition remains, coordinator restarts binding procedure. On the other hand, if sensor does not receive ACK frame, it tries again on the active channel (CC) and on the backup channel (BC), then it waits for a variable time (TD=DID*2ms) and it retries both BC and CC channels. Finally, it sleeps. So, there are maximum R=5 retransmissions in every cycle. If the failing condition remains on both channels for two consecutive cycles, a "rebind" procedure must be carried out.

The proposed approach has been directly compared with the WUSB network protocol suggested by Cypress. Models of both solutions have been designed using MATLAB™ environment from Mathworks to realize a discrete event simulator. Blind transmissions are assumed for both algorithms; in other words nodes transmit the packets without consideration of the channel state whether busy or not.

A simple statistical rule has been implemented to determine communication success or failure; for each sensor a random generated value, uniformly distributed in the range [0…1], is compared with a threshold (TH). TH simulates the overall failure probability of current transfer; in other terms, a value of TH=0.8 means that about eighty percent of nodes fail their transfer. As depicted in Figure 5, TH simulates a burst interference. It must be highlighted that position of bursts has been randomly generated, satisfying the need to reproduce asynchronous interferences as occur in a real communication scenario. Noise distribution has been spread over all available channels. In presence of bursts, error probability arises approximately up to one, which corresponds to a most likely failure in the communication between coordinator and sensor.

The communication cycle is partitioned into 5·M simulation steps, where M is the number of sensors. It has been allowed to vary the number of bursts (BN), their duration (BL) and floor noise (FN) in order to evaluate algorithm responses under different environmental conditions. BN and BL are strictly correlated. A variation of these parameters leads to similar noise density that can be expressed by the term $BN \cdot BL \cdot N^{-1}$.

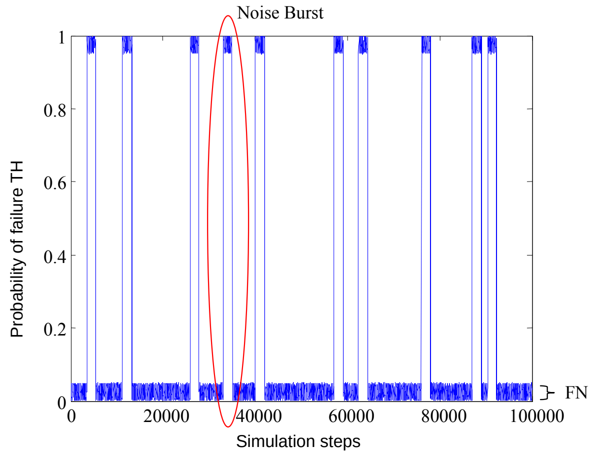

Fig. 5. Probability of failure (TH) generated on a channel. BN = 10, BL = 2000, FN = 0.05

Power dissipation has been estimated assigning a weight W to each phase according to their real current consumption; every retransmission presents a cost of W=1, while rebinding procedure charge is related on number of scanned channels and retransmission attempts. In this particular approach, considering a sub set of 13 channels and the worst case of double retransmission of bind packet on each of them, a maximum weight of W=26 has been fixed.

A performance index (Cost) has been considered to reflect power consumption due to retransmission and rebinding procedure. It is computed as the average power consumption of every sensor, according to equation (1), where N represents simulation steps and M is the number of sensors.

$$\text{Cost} = \frac{1}{M} \cdot \frac{1}{N} \cdot \sum_{i=1}^{M} \sum_{j=1}^{N} W_{i,j} \qquad (1)$$

Value of FN weakly affects Cost for both algorithms (FN<0.5); in fact, without any burst, Cost is 0.223 for WUSB and 0.227 for the proposed method if FN=0.2 (Cost=0.2 for both solutions if FN=0). Figure 6 shows the effect of a variable BN (that spans from BN=1 steps to BN=80 steps), with BL=20, FN=0.2, $N=10^4$ and M=10.

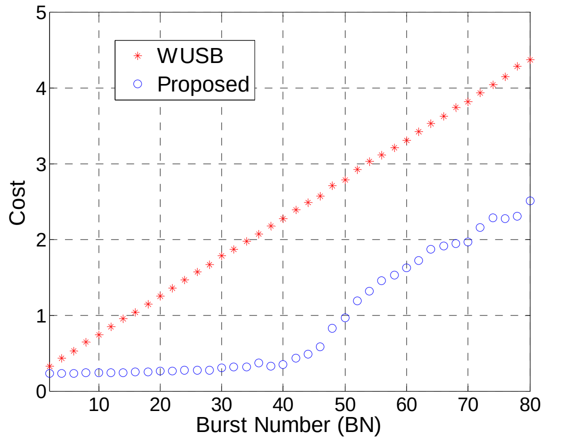

Fig. 6. Cost behavior due to BN variations @ BL=20, FN=0.2, N=10^4 and M=10

Traditional approach shows, obviously, a linear dependence and is more demanding than the proposed one. The proposed approach has a Cost that is unaffected by the number of burst BN till noise density is below 40%. If noise density increase too much, also the proposed suffers in finding a free RF channel and difference between methods reduce. Other simulations have been performed varying the burst length BL and a similar behavior results.

As a final remark, it can be said that the proposed approach works well in bursty noise condition, as it occurs in almost every real scenario, and it requires only a small computational overhead. Obviously this method is useful only if the network coordinator can be externally powered and it is able to constantly update the RF energy map.

3.3 Realized nodes

Several prototype nodes (coordinator, sensor) have been realized with the CY8C27443 processor, a mixed signal microcontroller integrating an 8-bit core capable of up to 4MIPS @ 24 MHz. It has a Harvard architecture with a 16 Kbytes code space and 256 bytes of user space. The coordinator code occupies about the 80% of the whole flash memory, while the sensor code is slightly smaller. In Fig. 7a is depicted a coordinator with only one mounted RF transceiver (software approach), while Fig. 7b shows a coordinator (hardware approach) equipped with two RF sections (CYWUSB6934, MC13192).

4 Experimental Results

Some quantitative considerations have been carried out; a shunt resistor (2Ω) and an instrumentation amplifier (INA110 with Gain=100) has been used to monitor current consumption. Supposing to have a 10kΩ resistive sensor, in sleep mode sensor node consumes ~50µA, in Tx or Rx mode current consumption (RF section + microcontroller) is about 80mA and 70mA, respectively, while in idle mode power consumption is in the order of few mA. Using a traditional battery (1 Ah) and Tcycle=1s, sensor life is in the order of one year (without retransmissions).

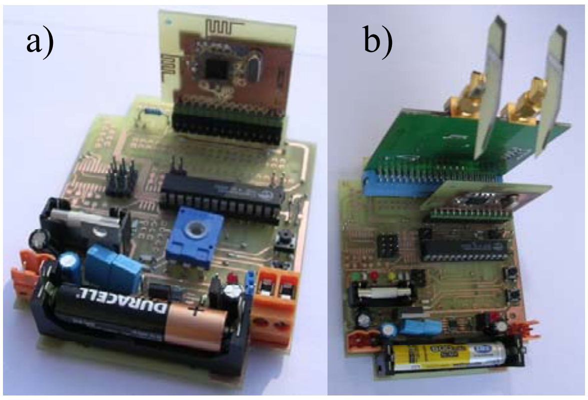

Fig. 7. The realized coordinator:
a) software solution b) dual receiver solution

A test bench has been developed to verify feasibility and performances of the RSSI. To emulate a RF crowded scenario, two different networks have been considered; vertices of an ideal square with 1.5 m long side have been occupied with two WUSB nodes (main network) and two nodes adopting IEEE802.15.4 technology (interfering network). Figure 8 shows RF power spectrum related only to IEEE802.15.4 traffic (2420 MHz channel).

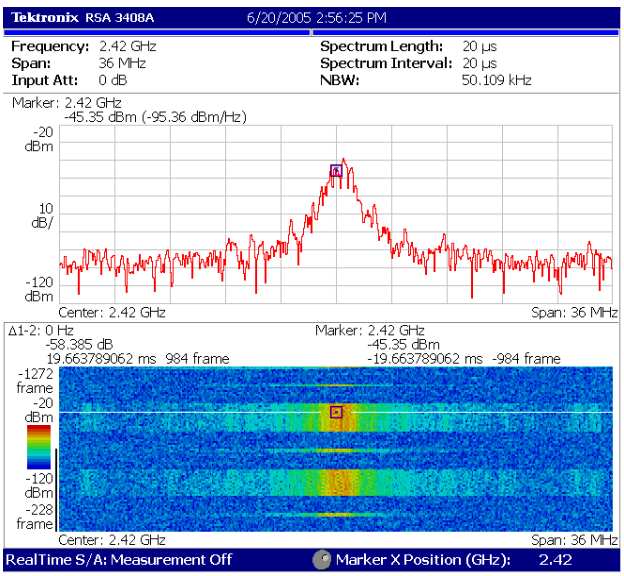

Fig. 8. RSA3408A grabbed image. Centre frequency 2420MHz, Span 36MHz

Spectrum estimation has been carried out with a Tektronix RSA3408A real time spectrum analyzer (probe in the centre of the square).

The WUSB network coordinator, with sniffing capabilities, is a dual receiver node placed in the centre; in particular, the Freescale MC13192 (IEEE802.15.4 compliant) and CYWUSB6934 have been used for channel noise estimation. MC13192 divides the available band into 16 channels 2MHz wide, 5MHz one apart from the other, while CYWUSB6934 considers 78 channels 1MHz wide. EN parameter, discussed in the previous section, is the channel-related ED value if MC13192 is considered. Otherwise, when computed with the CYWUSB6934, EN is evaluated as the RSSI summed over 3 adjacent channels; in this way the whole spectrum is divided into 15 bands 5 MHz one apart from the other, to be comparable with MC13192. The realized star topology network has only three nodes but, even if supposing a network with M=10 nodes and with a cycle time Tcycle=1s (100ms wide time slot), a sensor/coordinator transaction takes from 8 ms to 60 ms, leaving at least 40 ms for spectral estimation and diagnostic purposes. Adopting RSSI observation time of 128 μs, all 15 channels can be estimated in about 25 ms with the Cypress transceiver and in 9 ms with the Freescale one. Energy map can be refreshed every Tcycle, but suitable filters must be adopted to avoid too frequent backup channel changing. In our experiments the energy map is the mean value of 256 readouts. Figure 9 shows EN parameter related to both devices (MC13192, CYWUSB6934). In particular, it can be highlighted how both of them are able to furnish a response comparable with the high cost spectrum analyzer (see Figure 8) analysis.

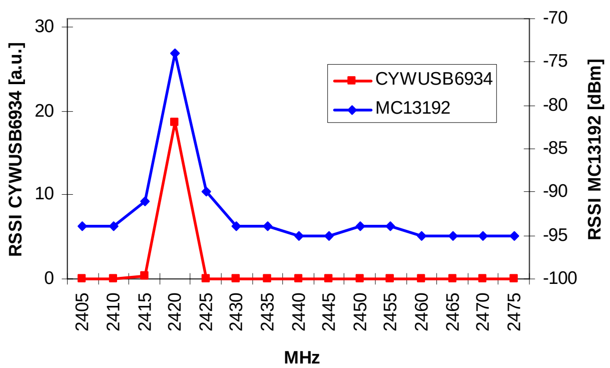

Fig. 9. RSSI evaluated with realized prototype

Maximum detected with the CYWUSB6934 transceiver is about the saturation value (31) times the intrusive traffic duty cycle, as expected. Concerning the Freescale transceiver, it gives an indication of the power received expressed in dBm, according to IEEE802.15.4 specs. Again, its value is about the power detected by the RSA3408A if the duty cycle of interfering communication is considered.

5 Conclusions

In this paper a novel approach for channel allocation in wireless sensor network has been proposed. The basic idea starts from the observation that most of industrial applications employ a star topology, where the master or coordinator node is always in the on-state and it is externally power supplied. An ad-hoc algorithm has been developed for dynamic channel allocation and extensive simulations have been carried out to demonstrate feasibility and advantages. The method success depends on the coordinator capability to estimate the RF energy map. In this paper, it has been suggested to process the RSSI value as the energy indicator. Some experimental tests have been conducted to show performances of power estimation by RSSI.

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