R-MAC: Reservation Medium Access Control Protocol for Wireless Sensor Networks

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***Abstract*— Energy consumption is a critical issue in wireless sensor networks as the battery of a sensor node, in most cases, cannot be recharged or replaced after deployment. In order to detect an event, a sensor node spends most of the time in monitoring its environment, during which a significant amount of energy can be saved by placing the radio in the low power sleep mode when no reception and/or transmission of data is involved. In this paper, we discuss the design of a new MAC protocol for wireless sensor networks, which mainly avoids overhearing, collisions, and frequent commutation between sleep and active modes. These issues are generally considered to be the most important reasons behind energy waste in heavy loaded conditions of wireless sensor networks. The proposed protocol, called Reservation-MAC (R-MAC), uses two separate periods during the communication process. In the first period, nodes compete for time slots reservation for their future transmissions, and in the second period, each node transmits its data or receive data from a corresponding sender. Once a node is aware of its transmission and/or reception time slot, it stays active only for these time slots and goes back to the sleep mode during the remaining time of the transmission period. In our experiments, the performance of the R-MAC protocol is studied in saturated conditions and compared with the well known S-MAC and T-MAC protocols. Depending on the traffic load, the proposed MAC protocol significantly improves the energy consumption compared to S-MAC and T-MAC.**

I. Introduction

Along with the recent advances in microelectronic technologies, wireless sensor networking is becoming a promising technology that will have a plethora of potential applications ranging from civilian to military domains, including environment monitoring, biological detection, vehicle tracking, and battlefield surveillance [4]. Such networks consist generally of a large number of sensor nodes that organize themselves into a multi-hop wireless network [3].

Wireless sensor networks are generally dense networks with nodes sensing a certain phenomena in the area of interest and reporting their observations to one or multiple base stations for further analysis. Once the sensor nodes are deployed, they need to establish a communication network among themselves for the subsequent information exchange between the sensor nodes.

Wireless sensor networks are often characterized by extreme constraints on size, cost, power, and timeliness. These characteristics impose, in turn, constraints on every aspect of the design of these networks, especially the protocol stack. Wireless networks inherently use broadcast media. All nodes in the network share one common communication medium. Therefore, a method for resolving contention, when multiple nodes require access to the medium, is necessary. A MAC protocol for wireless sensor networks should consume energy only when nodes are transmitting or receiving useful data and not when they are in idle listening mode. This property allows for an extended lifetime of nodes and ultimately of the entire network.

From the networking protocol design perspective, energy conservation in wireless sensor networks is possible via control the network topology and network layers. Concerning topology control, power consumption is reduced by enabling the nodes to turn off their transceivers, according to an adaptive duty cycle, when they are not needed for multi-hop communications [10]. At the network layer, energy saving can be achieved by energy aware routing and data aggregation [15].

In this paper, we discuss the design of a new MAC protocol for wireless sensor networks, which mainly avoids overhearing, collisions, and frequent commutation between sleep and active modes. These issues are generally considered to be the most important reasons behind energy waste in heavy loaded conditions of wireless sensor networks. The proposed protocol, called Reservation-MAC (R-MAC), uses two separate phases during the communication process. In the first phase, nodes compete for time slots reservation for their future transmissions. In the second phase, each node transmits its data or receive data from a corresponding sender. Once a node is aware of its transmission and/or reception time slot, it stays active only for these time slots and goes back to sleep mode during the remaining time of the transmission period. In our experiments, the performance of the R-MAC protocol is studied in saturated conditions and compared with the well-known S-MAC and T-MAC protocols. Depending on the traffic load, the proposed MAC protocol improves the energy consumption significantly compared to S-MAC and T-MAC.

The remainder of this paper is organized as follows. Existing related work on collision-based MAC protocols is discussed in Section II. The key elements of the designed MAC protocol are portrayed in Section III. To evaluate the energy consumption of the entire sensor network, simulations are conducted and the obtained results are presented in Section IV. Finally, concluding remarks and further research work are given in Section V.

II. RELATED WORK

Existing MAC protocols for wireless sensor networks can be broadly classified into two categories. The first category consists of TDMA-derived principles, where nodes are assumed to be synchronized and therefore access the communication channel by scheduling and reserving time slots. Scheduled-based protocols [2], [7], [9], [13] by nature preserve energy as they have a duty cycle built-in and an inherent collision-free medium access. However, their major drawback consists in their high complexity due to non-trivial problem of synchronization in wireless sensor networks. TRAMA [7] is a scheduled-based protocol that provides energy-efficient conflict-free channel access in wireless sensor networks. As a scheduled protocol, TRAMA is able to achieve good energy savings (at the expense of delay) but it has a fairly complex mechanism for assigning transmission slots to nodes. μMAC [9] shares a common architecture with TRAMA: the communication channel is divided into a contention period and a contention-free period. μMAC uses, however, a different slot mechanism and relies extensively on information provided by upper layers to improve radio utilization. Z-MAC [13] is a combination of TDMA and CSMA principles. It is shown that Z-MAC achieves high channel utilization and low latency than pure TDMA and CSMA. Z-MAC uses the concept of self-owned slot. A node has a guaranteed access to its own slot (TDMA style) and a contention-based access to other slots (CSMA style). In this way, collisions are reduced and better energy savings can be achieved. There are two basic components in Z-AMC. One is called neighbor discovery and slot assignment, and the other is called local framing and synchronization. In the neighbor discovery and slot assignment, a TDMA group is formed and a node is given a slot. A time frame is decided by the local framing and synchronization. Z-MAC introduces a new flexible time-frame rule without the need for global synchronization. However, it needs to perform global clock synchronization once at the setup phase.

The second category of MAC protocols is based on CSMA concepts in which sensor nodes strive for access to the medium [3], [6], [8], [12]. In this case, the communication establishment is based on an agreement between the sender and the receiver about when the medium comes available rather than when the scheduled time comes into affect. A contention-based protocols inherits good scalability, a feature highly required for wireless sensor networks, that supports node changes and inclusion of new nodes. Nevertheless, the contention-based approaches suffer from the energy inefficiency due to idle listening, collisions, and overhearing. S-MAC [3] is one of the best known protocols designed specifically for wireless sensor networks. S-MAC is a contention-based protocol and achieves energy conservation through three basic techniques: i) nodes periodically sleep instead of constantly listening to an idle channel; ii) radios are turned off when shared media is used for transmission between other nodes (overhearing avoidance), and iii) a message passing scheme is used to reduce contention latency for sensor network applications that require store-and-forward processing as data is transmitted over the network. Each node has a basic radio duty cycle that trades off between bandwidth and latency for energy savings. Bandwidth consumption is dramatically reduced as the duty cycle decreases since neighbors contend in smaller windows of time for transmission. Furthermore, significantly low duty cycles impose higher delays in the delivery of data and larger buffers to store data collected or received. S-MAC mitigates these problems when large messages need to be transmitted by fragmenting them and preventing a pair of nodes from sleep before all the fragments are transferred. The protocol requires periodic synchronization among neighbors so they can agree on sleep/active schedules. The use of radio fixed duty cycles in sensor nodes can waste considerable amounts of energy since the communication subsystem is activated even though no communication will take place. During periods of high activity, the radio must be turned on long enough to handle the traffic. However, as the load decreases, the radio will remain essentially idle. T-MAC [6], another contention-based protocol, addresses this problem by employing an adaptive sleep/active duty cycle for the radio operation. The protocol reduces idle listening by periodically transmitting all messages in bursts of variable length, and sleeping between bursts. The active period is ended up simply when no activation event is heard after a timeout. The timeout period defines the minimum amount of idle listening in a duty cycle. T-MAC suffers the same "high latency and large buffer size" problems as S-MAC when the duty cycle is very low. Besides these major problems, the synchronization is fairly hard to reach and clock drift may lead to unstable coordination, where nodes will never reach a consensus and therefore can never use their sleeping period. B-MAC [8] is another contention-based random access protocol. Different from the duty cycle controlled MAC protocols, B-MAC uses an adaptive preamble sampling scheme to reduce energy consumption and idle listening. The main feature of B-MAC is that it provides a basic access control platform and other MAC protocols can be built on top of it for customized and optimized energy savings as well as network performance. It is fully reconfigurable with a set of interfaces for the add-on MAC protocols. In P-MAC [12], a sensor node uses some networking activities information to formulate a pattern. Based on this information, a node may decide to have a long sleep, which may last for several time-frames. The pattern is generated when a node is awake and is sensing the environment. The pattern is exchanged among neighbors. In P-MAC the time-frame structure design has to accommodate the pattern exchange. Because P-MAC is able to adaptively sleep/wake up, it offers more energy savings under light loads and higher throughput under heavy loads compared to other contention based MAC protocols.

III. R-MAC Protocol Design

As reported in [3], several causes of energy waste must be taken into account in the design of an energy-efficient medium access protocol. Among these different causes, packets collision represents the first critical issue. In fact, when two packets are transmitted at the same time and collide, they become corrupted and therefore must be discarded. Transmitters will then attempt a new transmission which will consume again more energy. Another source of energy waste is idle listening. It happens when the radio transceiver is in listening mode awaiting possible data. The cost of idle listening is especially high in many applications of sensor networks where there is no frequent data to send. A third source is the unnecessary overhearing of packets that are destined to other nodes. Overhearing unnecessary traffic can be a dominant factor of energy waste when traffic load and node density are high.

According to [6], among all of the above mentioned causes of energy waste, idle listening is the most significant. However in reality, this depends on the traffic load within the network. Indeed, in case of low traffic load, nodes spend most of their time listening to an idle channel. However, in high traffic load, nodes spend most of their time in listening to packets of other nodes (e.g., overhearing). This issue has been already considered in S-MAC [3] and T-MAC [6]. However their proposed solution causes frequent switching between sleep and wake up modes which, in turn, consumes a considerable amount of energy.

In our proposed R-MAC protocol, we present a new solution to minimize the energy consumption by focusing mainly on the overhearing avoidance so that frequent switching between sleep and wake up modes will be avoided. This will help in conserving an important part of the otherwise-wasted energy of nodes, especially the heavily loaded ones (i.e., nodes near by the sink). The second considered problem in this work is the encountered collisions which can be frequent in a heavy loaded network. In the proposed R-MAC protocol, we adjust the listen-sleep durations according to the traffic load of the network and therefore reduce collisions while saving energy at the same time.

A. Basic scheme of the R-MAC protocol

Inspired by S-MAC [3] and T-MAC [6], our R-MAC protocol introduces two novel techniques to avoid frequent overhearing and switching between sleep and wake up modes in heavy loaded wireless sensor networks. The purpose of these techniques is to adapt the listen-sleep durations according to the traffic load of the network and therefore avoid collisions. The first main idea of our protocol is that each sensor node makes an advance reservation of the channel for its next transmission. This will allow nodes in the vicinity to know which transmitter and/or receiver is involved during each time slot for a large period of time. They then can schedule the instant where they have to be in a sleep and wake up modes. This behavior leads the nodes to avoid overhearing of several transmissions where they are not involved and therefore reduces frequent switching between sleep and wake up modes. For this purpose, we divide the listen period into two different variable periods. A reservation period of duration R and a transmission period of N time slots that fits N different transmissions. R is chosen by the first node that has succeeded its transmission of an RTS packet. Its value is chosen based on the traffic load observed by the winner of the channel and announced in the RTS packet. To avoid the idle listening, reservation and transmission periods are followed by a sleep period as in S-MAC. To Synchronize nodes so that they sleep at the same time, we add a synchronization period after the reservation period as shown in Fig. 1.

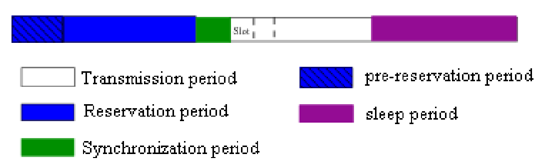

Fig. 1. R-MAC periods.

During the reservation period, a node behaves as in the CSMA/CA based MAC protocol with the well known RTS/CTS mechanism. If a node has data to transmit, it listens to the channel for the duration of $DIFS$. If the channel is sensed idle then it starts decrementing its backoff while the channel is idle. When the backoff reaches zero and the channel is still idle, the node transmits its RTS packet in which it indicates the time slot to reserve and the schedule of the periods. If after the duration $SIFS$, the considered node receives the CTS packet from the intended receiver then it waits for the end of the reservation period and then begins the transmission of its data in the reserved time slot. Notice that CTS packets also contain reserved slots as well as the schedule of periods. During the transmission period, nodes that have reserved their time slots will transmit their data only at the reserved time slots, and nodes that have data to receive wait for data during the adequate time slots. The rest of nodes can go to sleep since they have no data to transmit or to receive.

The second main idea in our proposed protocol consists in the variable duration of the listen and sleep periods according to the traffic load. By storing the number of transmissions occurred in a previous listen period, and by assuming that the same load of traffic is more likely to happen in the next listen period, nodes can adjust the duration of the next listen and sleep periods. To enhance the accuracy of the estimation of the next traffic load, the initiator node of R-MAC periods can also make use of the load observed in its waiting queue before transmission. Thus, R-MAC protocol can minimize collisions by expanding the listen period and reducing the sleep period when nodes estimate an increase in the traffic load.

In R-MAC, nodes are not synchronized with a control packet as in S-MAC and T-MAC. R-MAC periods are always determined by the first node which gains the access to the channel. The duration of these periods are locally disseminated using RTS and CTS packets of each communication. This implies that neighbors of transmitters and receivers will also follow the announced schedule. However, this may cause a problem in some cases, where nodes that do not participate in the upcoming communications, will switch to the sleep mode without informing their neighbors. In order to solve this problem, we introduce a new control packet, called GTS (Go To Sleep), which will be used by those nodes to send their schedule to their neighbors in the synchronization period.

B. Example

In the following we portray the behavior of the R-MAC protocol via an example. We consider the multi-hop wireless sensor network presented in Fig. 2

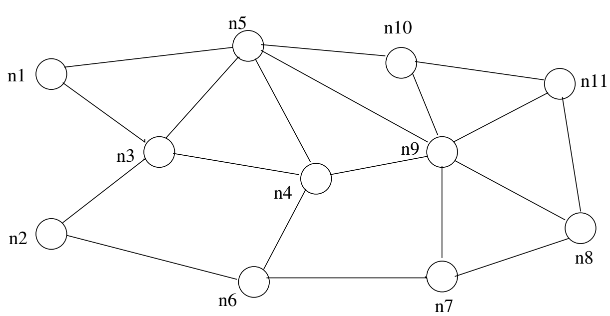

Fig. 2. A multi-hop wireless sensor network.

Let's consider a scenario where nodes n_3, n_4, n_5 and n_6 desire to transmit data to nodes n_4, n_9, n_{10} and n_4 respectively. If we assume that the number of time slots in a transmission period is $N = 3$ and that each node needs one time slot to transmit, then we can obtain the communication scenario presented in Fig. 3.

In this scenario, node n_3 initiates the cycle of periods P_3 (e.g., P_3 refers to a cycle of periods P initiated by node n_3) and reserves the first time slot of the transmission period of P_3 to send data to n_4. At that moment, nodes n_1, n_2, n_5, n_6 and n_9 are aware of the duration of each period of P_3 and know that the first time slot of the transmission period is reserved to the future transmission between n_3 and n_4. Later, node n_5 reserves the second time slot of the transmission period of P_3 to send data to n_{10}. Nodes n_1, n_3, n_4, n_9 and n_{11} will get also the information that the second time slot of the transmission period of P_3 is reserved for one transmission between n_5 and n_{10}. When node n_6 sends the RTS packet to n_4, it requests the reservation of the second time slot of the transmission period P_3. However, since n_4 knows that this time slot is reserved to the transmission between n_5 and n_{10}, it will not respond with a CTS packet. So as not to terminate the reservation period, n_4 sends an RTS packet to n_9 and reserves the third time slot. At the end of the reservation period: n_1, n_2, n_{11}, n_7 and n_8 transmits a GTS to inform their neighbors about the schedule of this period (P_3) initiated by n_3. By doing so, nodes inform their neighbors before entering the sleep mode. At the end of the synchronization period, node n_9 enters the sleep mode during the first and the second time slots. Node n_3 goes into sleep mode during the second and the third time slots. Node n_6 and others will go into sleep mode during the entire transmission period and so on. At the end of the transmission period, all nodes will stay awake or go into sleep mode for the duration designated by n_3 to avoid idle listening.

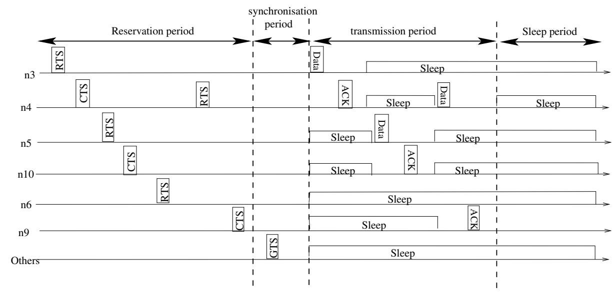

Fig. 3. R-MAC communication scenario.

To show the impact of this scheme on the avoidance of the frequent switching between sleep and wake up modes, we apply S-MAC protocol to the same example and we obtain the communication scenario shown in Fig. 4. If we compare this scenario to that of R-MAC (Fig. 3), we notice that in R-MAC, nodes n_3 and n_9 avoid two simultaneous communications and that in S-MAC they make an unnecessary switch between sleep and wake up modes. For other nodes, we remark that they make two unnecessary switches between sleep and wake up modes in S-MAC which are avoided in R-MAC by avoiding three communications at the same time.

C. Periods overlap

Since reservation periods are initiated by the first node which wins the channel among the contending nodes by sending an RTS packet, we can notice that in a multi-hop wireless sensor network an overlap of reservation and transmission

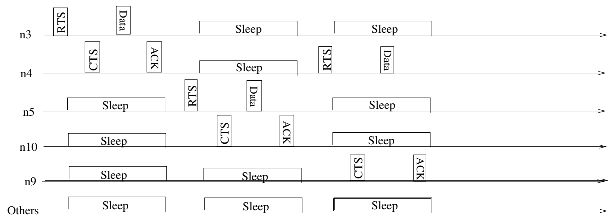

Fig. 4. S-MAC communication scenario.

periods can occur. Therefore, we have to identify each of them. For example, in the wireless sensor network topology shown in Fig. 2, node n_{11} can initiate a reservation period to send data to node n_8. Then node n_{10} can hear reservations from two different reservation periods (the one initiated by n_3 and the one initiated by n_{11}). Therefore, we need to have a mechanism to distinguish between them. In R-MAC protocol, we suggest that each node that has not heard an RTS packet (initiating a reservation period) can send an RTS packet with its ID for the initialization of a reservation period. If a sensor node wants to reserve time slots to transmit data, it must specify in which period it wants the reservation. In the above mentioned case, node n_{10} has both information regarding the reservation periods of P_3 and P_{11}. it can then choose one of the two.

IV. Simulations and Analysis

We evaluate the R-MAC performance by simulation using OPNET 11.5 [16]. We compare the performance of our R-MAC protocol against S-MAC and TMAC under the topology shown in Fig. 5 and in terms of three performance metrics: energy consumption, sleep percentage, and collision rate.

A. Simulation parameters

In this simulation scenario, we have made an abstraction of the top network layers into simple source and sink models for MAC - and PHY - centered simulation models, so there is no dynamic routing of packets to a base station. The topology shown in Fig. 5 is made of 32 sensor nodes (n_1 to n_{31}) and one sink node (n_{32}) randomly distributed over an area of 150x150m. To avoid the impact of any dynamic routing algorithm (with changing paths), routing follows the directed arrows as depicted in the figure.

B. Results and analysis

Results shown in Fig. 6 demonstrate that the overhearing and the switching between sleep and wake up modes, provided by the avoidance technique developed in our R-MAC, provides longer sleep opportunities than in S-MAC and T-MAC protocols. This is particularly true when the network is heavily loaded with high data traffic rate. However, in case of low data traffic rate, T-MAC outperforms both S-MAC and R-MAC. Regarding the energy consumption, Fig. 7 shows that R-MAC outperforms S-MAC and T-MAC again in case of high data rate traffic. Indeed, the R-MAC protocol avoids in many cases the overhearing events as well as a number of commutations between sleep and wake up modes. In low data

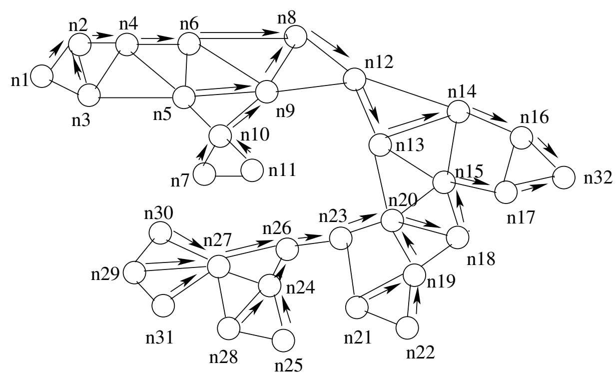

Fig. 5. Wireless sensor network topology with 31 sensor nodes and 1 sink.

rate, T-MAC outperforms again both S-MAC and R-MAC. Concerning the data collision rate, Fig. 7 shows that R-MAC protocol avoids totally data collisions. This free collisions advantage is obtained bye the advance reservation of time slots during the transmission phase and bye the adjustment of the period's duration of each phase according to the traffic load.

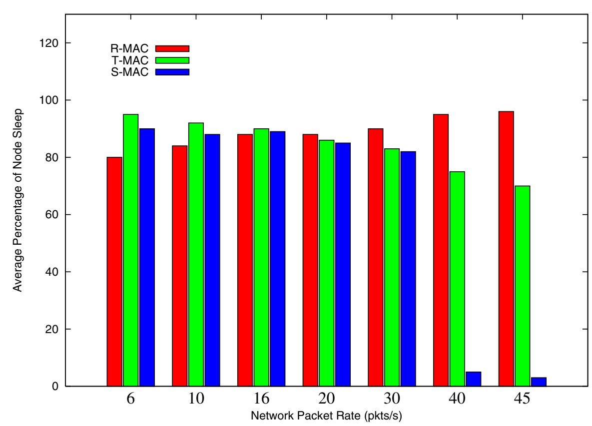

Fig. 6. Average node sleep rate.

V. Conclusion

In this paper, we have presented a reservation based MAC protocol, dubbed R-MAC. In the design of the proposed scheme, our focus was on the avoidance of overhearing, frequent commutation between sleep and wake up modes, and data collisions. This aims at minimizing the energy consumption in saturated conditions. By choosing to use a channel reservation scheme, nodes can anticipate next scheduled transmissions during the listen period and therefore make accurate decisions on the timing to turn off their radio. R-MAC protocol also adjusts the duration of the sleep and active periods according to the traffic load in order to avoid data collisions. Simulation results show that R-MAC outperforms S-MAC and T-MAC in conserving energy of sensor nodes in heavy loaded wireless sensor networks.

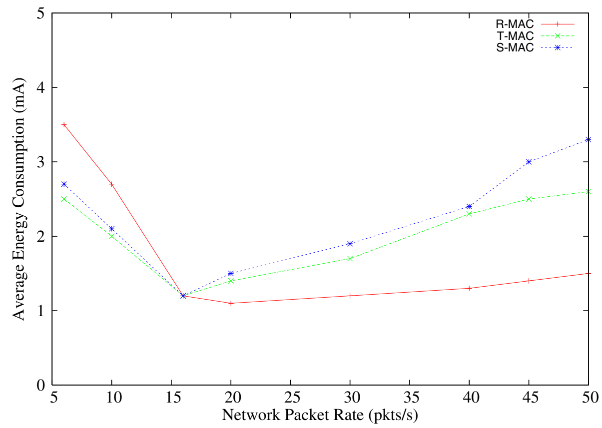

Fig. 7. Energy consumption.

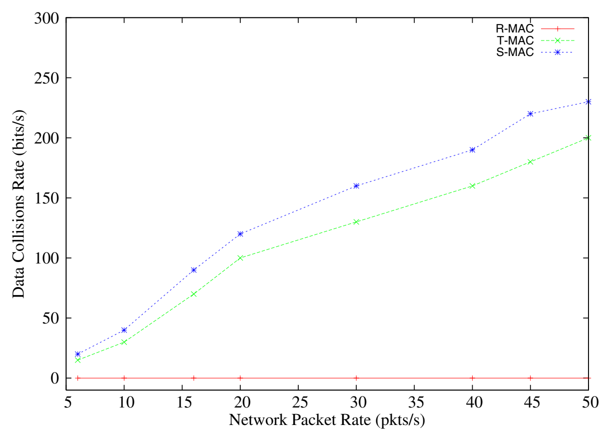

Fig. 8. Data collision rate.

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