Power Conservation in ZigBee Networks using Temporal Control

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Abstract—**This paper addresses power reduction in wireless sensor networks (WSNs), proposing an application-level solution for the IEEE 802.15.4 compliant ZigBee protocol. Currently, ZigBee protocol supports the least power-consuming 'sleep' mode of operation only for end-nodes that do not route packets. This significantly limits ZigBee's WSN applications. This paper presents a ZigBee-based power-conserving network design in which a multi-mode scheduler can be used at the application-level for all network nodes that brings the whole net up and down. This allows all nodes to 'deep sleep', hence increasing the per-node lifetime, leading to an increased overall network lifetime. Results of network simulations with a Rate Monotonic-based Scheduler, schedules operating times for various nodes in the entire network, setting the devices to the lowest power operating mode – sleep mode – for all other times when no operation needs to be performed. When the network wakes up, all nodes necessary for a particular scheduled transmission awake and rebuild the ZigBee network. The paper presents power savings estimates from simulations showing significant advantages over standard ZigBee.**

Index Terms –**Low Power Sensor Networks, ZigBee**

I. Introduction

Energy consumption is among the biggest challenges in WSNs. ZigBee [Kinney-03] is a protocol that supports low power, low cost, low data-rate operation of its network devices. Major players in the electronics industry, such as Motorola, Samsung and TI, are members of the ZigBee Alliance– the organization that develops the ZigBee specifications. ZigBee's single chip solution, which constitutes a microcontroller and RF communication capability, makes it a protocol with great potential for use in resource-constrained monitoring and sensing applications.

ZigBee networks have 3 types of devices [Marsden-05] – coordinator, router and end-device. As it stands today, the protocol is not designed to support sleep mode of operation in the entire network. The end-devices can operate in sleep state, but in order to guarantee reliability the routers need to remain on and constantly listening for activity. If this protocol is to be used in WSN applications, the sleep mode of operation will clearly be required in all ZigBee devices.

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This paper summarizes the results of [Viswa-06], which proposes a method of controlling the entire network from the application-level. Irrespective of the type of network protocol, the design proposed in this work is capable of saving network power significantly. Section 2 deals with the concept of Temporal Control in ZigBee, section 3 discusses the simulation implementation, section 4 presents some of the results obtained from our tests and section 5 is the conclusive part that talks of possible future work in this regard.

II. Temporal Control Concept in ZigBee

Sensor nodes operate at really low duty cycles with low latency. If the network nodes wake up, perform their tasks and then revert back to sleep state, this would be very beneficial in terms of extending network lifetime. Although this concept of "sleep state" is not new in WSNs [Berkeley-01, Cerpa-estrin-02, Lin-et-al-04], this work is the first to develop an approach to adapt it in the ZigBee protocol. Implementing this concept in ZigBee will require 2 major changes. Firstly, the DSSS nature of ZigBee's underlying 802.15.4 cannot support a means for one node to "wake" its neighbors, so we must have an approach by which the nodes are scheduled to wake up at the appropriate time. Secondly, the ZigBee network does not support any type of suspended state for router nodes so we literally loose the mesh network when we sleep. Thus after waking, the ZigBee network must reestablish itself including the network routing tables. Compared to prior work on sleeping networks, this may seem expensive, but the experiment results on this Temporal Control model, including rebuilding network, show it has lower power consumption than Standard ZigBee.

III. Temporal Control ZigBee Network Simulation

To provide sleeping, we need to develop a local scheduler on each node. Given that schedule, the nodes can wake up and do their tasks, including network tasks when needed for their own operation, or when needed to route. The simulation proposes 4 operating modes for ZigBee nodes constituting the various tasks a node might be required to perform. Modes 0 and 1, for instance, are *local tasks* (tasks that nodes perform on themselves) for the node to check its device clock for overflow, and for data-sampling/saving, respectively. Modes 2 and 3 are *network tasks* (tasks requiring data communication/routing over the network) to transmit a sample set captured by that node and to route samples that were captured by another node, respectively. When a node is not operating in any of the above 4 modes, then the node is set to sleep state, conserving power until the schedule says it needs to wake up to perform any of the above mentioned operations. Importantly, the global scheduling operations determine when intermediate nodes need to wake up to allow construction of a subnetwork sufficient to support the required transmissions. An example is shown in figure 1.

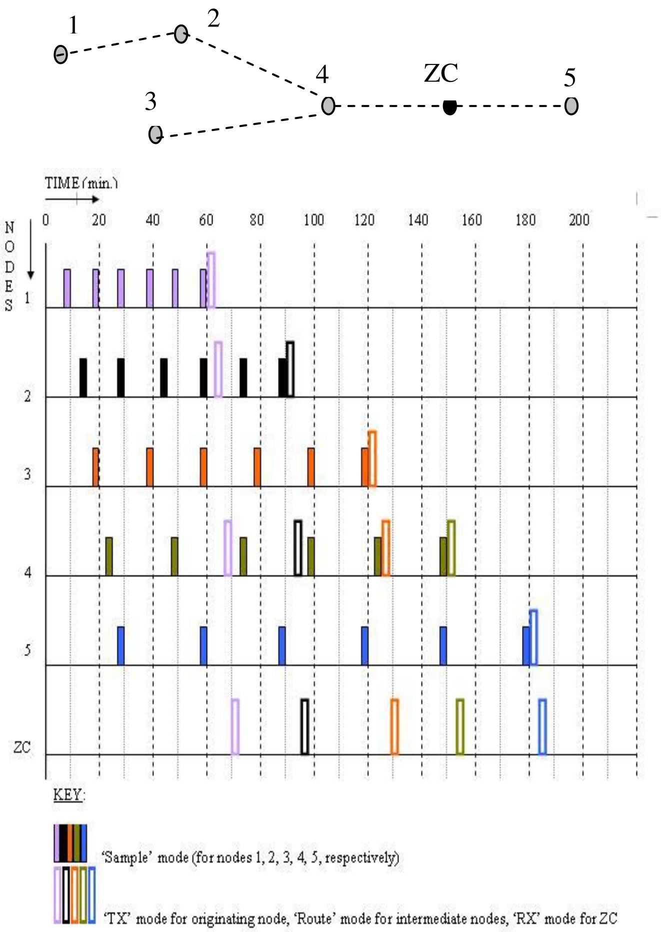

Figure 1: A simple 6 node network, and the resulting schedule. In the example nodes 1-5 sample data every 10, 15, 20, 25 and 30 minutes respectively and must transmit their stored data every 60, 90, 120, 150 and 180 minutes respectively. The hollow bars in the schedule show when nodes wake up to support transmission of data for other nodes.

To determine the schedule for each node, a global scheduler is run patterned along the lines of the Rate Monotonic Scheduler. The simulations herein are defined by providing certain parameters, like network shape (fence or grid) and dimensions (length and breadth). From this information, a network is generated with the various ZigBee nodes placed in appropriate positions. Routing information is determined from each node to the root (coordinator) node. There are also several other tunable parameters including – duration of simulation, data throughput, payload size and network rebuild/reestablish time – that could be modified by the user in order to determine the effect on network performance and power consumption. The per-node parameters used were determined from operational experiments using a chipcon CC 2420 ZDK with five CC 2420DB boards. An enhanced transmission approach using ZigBee, from [Narayan-06], was used to obtain the sustained 70Kbps transmission rates. As a result of the simulation, the power consumed by the network nodes in each operating mode was computed for both operating models (Temporal and Standard). The amount of power consumed by a particular mode of operation is a function of the duration of that mode. Power calculations were therefore done in milliwatt-hours (mW-hr). Average power consumed by the entire network in both models, network utilization and several other statistics were also generated. Some of these results are shown in the next section. Details on implementation, experimentation, more results and discussions can be obtained from the thesis work in [Viswa-06].

IV. EXPERIMENTAL RESULTS

Experiments were conducted on different network configurations and sizes, some of which have been discussed in this section. Initial runs were on a 10x10 grid network, consisting of a single coordinator (root) with all other nodes configured as routers. The coordinator was one corner and dedicated end-devices were not included in these runs. All experiments presume 70,000 bps transmission, 1sec rebuild time and a simulation length 8100sec. Unless otherwise stated they presume 1KB payloads.

As shown in Table 1, there is a noticeable difference in the average power consumption between the Temporal and Standard ZigBee models. The power values are very close for smaller transmission time-periods (or higher frequencies of transmission). The most expensive task for a ZigBee node is to rejoin the network, reestablish its neighbor information and routing tables. This task happens each time the node wakes up from sleep. Hence the less frequently it needs to come up, the more savings in power.

Average seconds between transmit	Temporal Enhanced ZigBee mW-hr per node	Standard ZigBee mW-hr per node
2.0	430.1991	440.8821
3.0	408.2858	441.1238
3.5	336.6767	440.9571
5.5	260.1733	440.7154
8.0	237.0017	440.5932
10.5	204.5193	440.4710

Table 1: Average time-periods for transmission vs. Average per-node power for a 100-node grid.

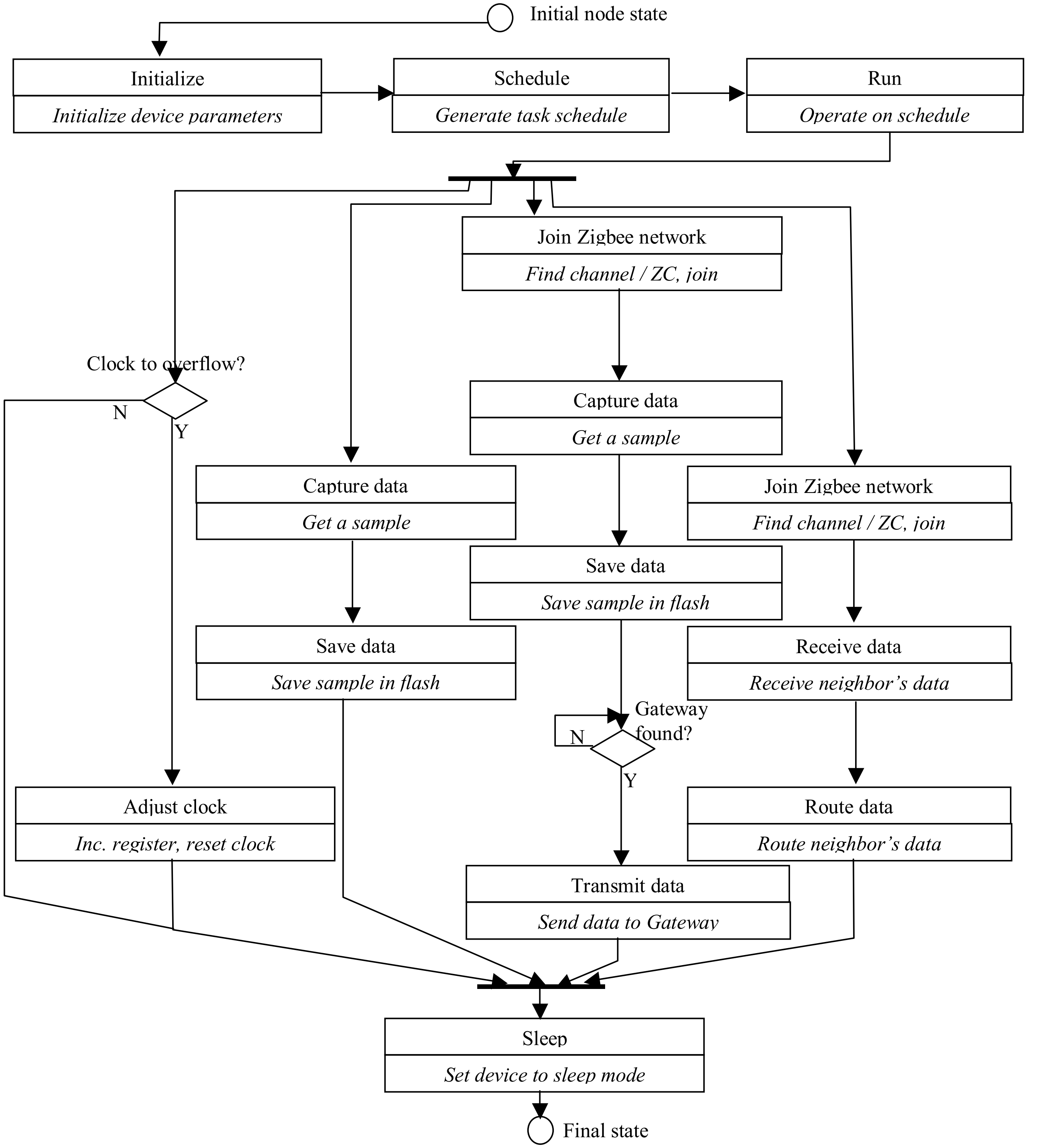

Figure 2: Network Node State Diagram

Based on our observations, we developed the following equations to determine whether the Temporal Enhanced ZigBee operation is advantageous for a particular scenario:

$P_{temporal}$ = [(Time rebuilding network)*(Power for network rebuild)] + [(Time sleeping)*(Power sleeping)]+[(Time scheduling)*(Power scheduling)]

$= [T_{rebuild} * P_{rebuild}] + [T_{sleep} * P_{sleep}] + [T_{sched} * P_{sched}]$

$P_{standard}$ = [(Time rebuilding network)*(Power for idle)] + [(Time sleeping)*(Power for idle)] + [(Time scheduling)*(Power for idle)]

$= [T_{rebuild}*P_{idle}] + [T_{sleep}*P_{idle}] + [T_{sched}*P_{idle}]$

By plugging in the corresponding time durations into the above expressions, the 2 power factors, $P_{temporal}$ & $P_{standard}$, can be computed. Whichever power value is lower would be the better choice for a particular network. The tradeoff is between the cost of idle operation in Standard ZigBee versus the cost of rebuilding the network each time a Temporal ZigBee node wakes up from sleep mode. Normally, sensor networks operate at very low duty cycles – time spent joining/transmitting/routing is far lower than the time spent sleeping. Hence, it would not be wrong to generalize that in most practical WSN applications the Temporal Enhanced ZigBee power consumption will be a lot less compared to the Standard ZigBee alternative.

KB	Network Utilization	Temporal Enhanced ZigBee mW-hr per node	Standard ZigBee mW-hr per node
0.5	0.5432%	31.58	440.40
5	0.2716%	29.12	440.00
50	1.6296%	150.92	551.05
500	16.0247%	12904.16	13190.46

Table 2: Payload vs. average per-node power consumption for a 100-node fence network.

Tests were also conducted to measure the effect of payload size on network power consumption. WSN payloads are generally very small (often only a few 1000 bytes), hence requiring a fractional amount of time for transmission. But packets are often collected and send in a bulk transmission mode. From the observations in Tables 2 and 3, a large amount of power is saved in the Temporal model for either network configuration type. Even at 50 KB payload size (which is already pretty large for a sensor network), the Temporal model seems to consume only about 1/6th the average power of Standard model (in a grid) and about 1/3rd the average power of Standard model (in a fence).

KB	Network Utilization	Temporal Enhanced ZigBee mW-hr per node	Standard ZigBee mW-hr per node
0.5	0.5432%	29.13	440.17
5	0.2716%	28.01	440.00
50	1.6296%	84.21	491.01
500	16.0247%	5987.74	6339.51

Table 3: Payload vs. average per-node power consumption for a 100-node grid network..

The readings were from ZigBee grid and fence network configurations in which all the network nodes were ZigBee routers (except the one coordinator). However, there might be applications requiring the core network nodes to be routers, with all boundary nodes being ZigBee end-devices. Such networks with end-devices might have a considerable impact on the average network power. If the router state could be saved, replacing boundary routers with end-devices, then all boundary nodes would only have to rejoin the network each time they wake up from sleep mode. Network 'rejoin' (wake up and associate with nearest router) is a lot less expensive than network 'rebuild' (wake up, reestablish network, reconfigure routing tables and list of neighbors). Hence, using end-devices at the boundaries would reduce the average network power consumption for this model. In contrast to this, using end-devices at the boundaries in a Temporal ZigBee network model would mean that each time an end-device wakes up, it would have to rejoin with its parent router and would not have to be up during the time taken by the parent router to rebuild its network, reestablish all its neighbors and regenerate its routing table information.

Mean packet separation (seconds)	Mean Temporal Enhanced Zigbee mW-hr per node	Mean Standard Zigbee mW-hr per node	Variance Temporal Enhanced Zigbee (mW-hr)	Variance Standard Zigbee (mW-hr)	Power savings ratio (%)
1.5	29.1331	257.49	0.2082	42038.50	783.87
2.5	28.7061	257.48	0.5174	42047.06	796.95
4.5	28.2408	257.46	0.5431	42053.70	811.68
6.5	28.2733	257.46	0.7508	42053.08	810.63
8.5	27.9275	257.45	0.5724	42106.71	821.87
10.5	27.8861	257.45	0.6439	42058.10	823.24

Table 4: Effect of varying transmission time-periods on average power for a 100-node grid.

Mean packet separation (seconds)	Mean Temporal Enhanced Zigbee mW-hr per node	Mean Standard Zigbee mW-hr per node	Variance Temporal Enhanced Zigbee (mW-hr)	Variance Standard Zigbee (mW-hr)	Power savings ratio (%)
1.5	29.3303	435.84	0.0137	1704.57	1385.99
2.5	29.2567	435.84	0.0666	1704.90	1389.73
4.5	29.2178	435.84	0.0722	1704.90	1391.75
6.5	29.1767	435.84	0.1537	1705.11	1393.81
8.5	29.1372	435.84	0.1151	1704.90	1395.83
10.5	29.1244	435.84	0.2139	1705.16	1396.49

Table 5: Effect of varying transmission-frequency on average power for a 100-node fence with 1KB payload.

KB	Mean Temporal Enhanced Zigbee mW-hr per node	Mean Standard Zigbee mW-hr per node	Variance Temporal Enhanced Zigbee (mW-hr)	Variance Standard Zigbee (mW-hr)	Power savings ratio (%)
0.5	28.83	257.59	3.04	42091.23	793.25
1	27.88	257.44	0.64	42055.74	823.24
5	27.88	257.44	0.64	42055.74	823.24
10	31.56	260.18	17.74	42692.13	724.14
50	75.68	300.48	1961.26	52867.87	297.03
100	229.97	449.07	33718.40	112935.80	95.27
500	5097.24	5271.63	20832783.93	21516156.15	3.42

Table 6: Effect of varying payloads on average power for a 100-node grid.

KB	Mean Temporal Enhanced Zigbee mW-hr per node	Mean Standard Zigbee mW-hr per node	Variance Temporal Enhanced Zigbee (mW-hr)	Variance Standard Zigbee (mW-hr)	Power savings ratio (%)
0.5	31.57	436.23	1.02	1708.34	1281.41
1	29.12	435.83	0.21	1705.06	1396.49
5	29.12	435.83	0.21	1705.06	1396.49
10	38.56	443.12	6.31	1764.39	1049.11
50	150.84	546.80	712.35	3122.92	262.51
100	542.82	925.90	12290.51	16522.60	70.57
500	12895.36	13177.49	7612667.80	7563773.94	2.19

Table 7: Effect of varying payloads on average power for a 100-node fence.

Tables 4 and 5 present the observations from experiments conducted in this new network configuration (with end-devices at boundaries) in both Temporal Enhanced and Standard ZigBee networks. The readings show the variation in the average power consumed per network node with changes in the average transmission time-periods, in the grid and fence network configurations.

The above observations show a Power Savings Ratio (PSR) of around 800% for a ZigBee grid and PSRs of around 1400% in a ZigBee fence. Irrespective of the changes in packet transmission intervals, the power savings are very significant, so even allowing for some end-nodes the temporal enhanced ZigBee has a significant advantage.

Another interesting set of observations would be the effect of payload sizes on average power consumption in this network configuration (with end-devices at boundaries). Table 6 and 7 are for 100-node ZigBee grid and fence network configurations. The PSR values clearly show the potential savings from using the Temporal Control model with lower, sensor-network-like payloads (<50KB). Unlike in the previous scenario of changing packet transmission frequencies, here the variation in payload sizes has a significant effect on mean power values and therefore on PSRs. For lower payload sizes, the Temporal model nodes spend lesser time transmitting/receiving and routing packets, hence operating in deep sleep for longer periods of time therefore showing considerable savings when compared with the corresponding readings for the Standard ZigBee model. In comparison, as payload sizes increase (~100s of KB), network nodes in both network models end up spending most of the time staying awake and transmitting data, hence leading to hardly any difference (indicated by the very low PSR values). But again, payload sizes of several hundreds of KB are not typical of WSN applications.

V. Future Work

The ZigBee Protocol is the only international standard wireless sensor network protocol in existence, catering to the specific needs of low-power, low-cost, low maintenance monitoring and control systems with talks of using it in sensor networks. While already well suited to simple control systems, if the ZigBee protocol is to be used in WSN applications, it cannot afford to have routers operating powered up in Idle mode. Routers will need to be capable of running in lower power sleep modes, waking up in time to perform any of their assigned tasks and then going back to sleep mode. This effort clearly brings out the fact that providing Temporal Control by creating a schedule of operations for all routers in a ZigBee network would significantly increase network lifetime, in comparison with the current Standard ZigBee approach.

This work was mainly done as a proof-of-concept to demonstrate, by way of simulations, the need for and value of implementing Temporal Control in ZigBee. As a result, the design still needs enhancements in some ways. In this simulation, static routes are determined for source to sink routing. These routes are simply determined based on path costs, lowest cost being the chosen route. It would be a useful improvement to find a way to compute multiple routing options and compare them in order to determine how many nodes need to be brought up and how many are already up. This way, a route with greater cost might turn out less expensive if fewer nodes need to be brought up as opposed to picking a route with lower cost where more nodes need to come up. This *routing optimization* mechanism might help save more power in the Temporal Control model.

Another possible enhancement to the routing mechanism might be to have multiple routing options for communication from source to sink. This way, if any of the nodes in one routing path is down and cannot be woken up as a result of some node defect, then there will be nodes in alternate routes that the scheduling algorithm could choose to wake up. This would provide *routing robustness* to the currently proposed model.

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