Using Network Calculus to Model Energy Harvesting Wireless Sensor Networks (Extended Abstract)

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Nowadays sensor nodes are commonly used for surveillance purposes. A node's sensing unit usually covers a specific area in order to monitor characteristics like temperature, humidity, or movement. The resulting measurements are then reported to a central entity for evaluation. However, the area sensed by a single device is typically not covering the whole region of interest so multiple sensors are needed. Their composition in conjunction with the ability to wirelessly communicate and thus collaborate even allows for the surveillance of a generally inaccessible region like a forest or a glacier where it is infeasible to install an infrastructure or maintain the devices at all. Yet, wireless sensor networks often still have to meet predefined requirements like a maximum reporting delay of an event or a sufficiently long network lifetime in order to achieve their designated task.

The network lifetime is commonly defined to end as soon as the first node's battery is depleted. Consequently there has been plenty of work concentrating on increasing the operation time of sensors. On the one hand, there are node-local efforts to conserve energy such as power management that may shut down parts of the device during a period of time, duty cycling that may shut down the whole device, voltage scaling and transmission speed adjustment that adapt the power consumption to the workload and transmission range adaptation optimizing the energy used for the expensive wireless communication. On the other hand, there are network wide concepts pursuing the same objective by preventing the so-called hot spot problem stating that the nodes near the sink are depleted earlier because of relaying more traffic. Among these concepts there are routing protocols and multiple as well as mobile sink solutions that aim to evenly distribute network traffic without unacceptably degrading the delay performance.

These efforts shift the network's end of life into the future but they do not solve the underlying problem of a decreasing level of available energy at a node's disposal. Thus lifetime remains finite as exhausted batteries are inevitable if it is impracticable to recharge them. However, in recent times technological advancements like energy harvesting made it feasible to recharge devices without the need for a sophisticated infrastructure. With energy harvesting, sensor nodes can constantly replenish their battery with environmental energy such as electromagnetic radiation or solar power. Thus this technique allows nodes to operate past the time their energy consumption exceeded their initial energy budget.

We aim to use network calculus to model energy replenishing sensor nodes in order to derive their service curves. By concatenation of the individual service curves we are then able to define the end-to-end service for a specific data flow and thus bound the time it takes until a measurement or event is reported to the sink. This allows to check if requirements are met and enables to take appropriate action in the network design already before deployment.

As mentioned above, harvesting defines the energy replenishment of a sensor node and therefore restricts the possible service by upper bounding the energy that can be spent. On the other hand, the service that is required by a flow defines how much energy is spent by the sensor node and how much could be preserved to increase performance in the subsequent periods of operation. Our main effort lies in modeling the mutual dependency between performance and energy consumption in order to derive an accurate service curve representation.

During the time the sensor is running on its initial energy budget, it can offer forwarding services according to a fixed service curve β. The delay an arriving data flow that is characterized by the input process A suffers when crossing a sensor node on its path to the sink is then lower bounded by the horizontal deviation of its arrival curve α and the sensor's service curve, i.e., $h(\alpha, \beta)$. However, as soon as the battery was depleted first, the service is additionally depending on the sensor node's energy replenishment and we cannot simply use the ordinary network calculus descriptions for service and arrival to derive the delay bound. The service demand and thus the energy consumption of the data flow A must be characterized in order to assure for any time instance that the energy budget is not exceeded and the service curve has to be adapted accordingly.

Energy consumption can be characterized by the output of the sensor node $A' \geq A \otimes \beta$. If the sensor's service β would cause an output that is too energy exhaustive, we aim to limit the amount of data that enters the system and thus can consume energy in order to prevent the depletion of the sensor's battery. We call this arrival restriction A_{restr}. For any time instance the effective input served by a node's forwarding capabilities is then bounded by $A \wedge A_{\text{restr}}$ and the output accordingly by $(A \wedge A_{\text{restr}}) \otimes \beta$ which is guaranteed to drain less energy than available. Our model for the mutual dependency therefore resembles a feedback network [2] where the input depends on the output and vice versa.

The problem of a service restriction according to the behavior of a replenishing energy source resembles a window flow control mechanism [1]. Just like a window flow controller (WFC) we want to limit the amount of data that enters the system, but in contrast to a WFC we do not intent to do so according to a predefined and well-known artificial restriction. Thus we aim to model a more general setting of external restrictions to a sensor node's service.

References

1. Rajeev Agrawal and Rajendran Rajan. Performance bounds for guaranteed and adaptive services. IBM Research Report, 1996.
2. Francois Baccelli, Guy Cohen, Geert Jan Olsder, and Jean-Pierre Quadrat. *Synchronization and Linearity: An Algebra for Discrete Event Systems.* Wiley, 1992.