



## Original papers

## Real-time and clock-shared rainfall monitoring with a wireless sensor network

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## ABSTRACT

Rainfall is recognized as one of the most important factors in hydrology. Particularly, investigation of the tempo-spatial variation patterns of rainfall and their effect on environments has attracted more and more attention in recent. Because of the limitations in both human costs and existing rainfall monitoring devices, however, it is very hard for researchers to collect real-time rainfall data from large-scale geographical areas. This paper designs and implements RealRain, the first real-time wireless system of monitoring rainfall, which explicitly serves as an effective and efficient scientific instrument for domain experts to facilitate the measurement of large-scale and real-time rainfall. With the tipping bucket as the rainfall signal detecting device, RealRain employs commercial embedded wireless platforms to record and collect rainfall data automatically. Especially, RealRain involves a tree-based time synchronization scheme. For practical account, we also propose a sample-send-store scheme to improve the data reliability of RealRain under potentially harsh environments. *With RealRain, end-users can remotely retrieve the real-time and fine-grained rainfall data under a unified timeline.* Finally, we implement a proof-of-concept prototype of RealRain, which is completely driven by rainfall events and can automatically feed the data to users. The preliminary laboratory results and analyses demonstrate the feasibility and the efficacy of RealRain.

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## 1. Introduction

Rain is an important form of water cycle and contributes to deposit a large fraction of fresh water on the Earth. In nature, rain or rainfall is the *sine qua non* for almost all the ecosystems, including forests, grasslands, wetlands, deserts, and even our human beings, to survive with desirable ecological conditions. The rainfall information is therefore one of the most important factors in hydrological analysis and modeling (Hernandez et al., 2000; Aikawa et al., 2009; McMillan et al., 2011; Fehmi et al., 2014; Hasan et al., 2014). Often rainfall is measured daily or even monthly, either by the receptacle-and-gauge mechanical device or by the electrical/optical weighing device (Colli et al., 2013). Domain researchers or end-users can roughly estimate the rainfall with a few rainfall-detecting devices deployed in area-small sites. With the rainfall information, end-users can infer cause-and-effect relationships *on the macro level* between rainfall and other physical

events (e.g., the effect of rainfall on net primary production and soil moisture content), but sometimes, they have to manage rainfall-detecting devices and record rainfall data by hand after rain stops. Even though some applications use apparatuses able to monitoring rainfall remotely, those apparatus themselves need to equip with the independent transceiver supporting long-distance communications, which will increase both the package size and the cost in large-scale deployment.

Recently, however, there are more and more concerns on obtaining fine-grained and real-time rainfall information *on the micro level* in an effective and efficient way. First, though the total rainfalls over long periods did not differ significantly, the distributions of the rainfall within short terms varied considerably from day to day, or even from minute to minute (Baptista et al., 2015), especially when heavy rainfall happened. Second, it is now urgent in the research community to identify the rainfall patterns of tempo-spatial variation, by which hydrologists can well understand the actual effects of rainfall on other environmental factors. Hence, retrieving the real-time rainfall data from a larger geographical area has literally become a key requirement in hydrology. Below are several typical scenarios crying out for real-time or large-scale rainfall

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monitoring. Soil loss is strongly correlated with rainfall (Zhu et al., 2012; Pelletier et al., 2012; Baptista et al., 2015). With only the rainfall observation based on long-term statistics, however, hydrologists cannot give accurate and fine-grained models that profile the time-varying effect of rainfall on soil losses. Also, analyzing and quantifying the actual reduction with rainwater usage in urban areas need real-time and city-scale rainfall data (Talebpour et al., 2011; Umapathi et al., 2013). For early-warning applications in rainy days, such like the debris-flow warning and preventing application, the real-time rainfall data from large mountain area is extremely necessary for researchers to accurately and timely predict when, where and how the debris flow will occur (Chang et al., 2011; Peng et al., 2014).

Unfortunately, already-existing rainfall-detecting devices as well as methodologies are often insufficient to support the real-time and large-scale environmental monitoring that needs rainfall information. On the one hand, most of commonly-used rainfall-detecting devices, such like the rain gauge, often indicate only the rainfall in a local site of small area—strictly, the output of such a device can only characterize the rainfall at the point where this device locates. Therefore, a great deal of rainfall-detecting devices need to be deployed in the field, in order to achieve large spatial coverage. Nevertheless, prior approaches do not make sense in large-scale scenarios because they require more human resources in data acquisition. On the other hand, the rainfall data, usually buffered at detecting device, cannot be retrieved until the rain stops, which merely supports the off-line rather than the online analysis. For devices with small storage capacity, they are very prone to experience data overflow during long-term rainfall—early samples have to be erased to buffer the subsequent ones. In conclusion, the means to detecting rainfall nowadays is unable to efficiently capture the spatial and temporal variation of rainfalls within the region concerned by researchers. Noticeably, the weather radar system (Doviak and Zrnica, 1993) is a very powerful weather monitoring infrastructure, almost exclusively used by meteorological departments of government, but it is hard to be applied here and there in the real world because of the high cost in deployment and maintenance.

Another significant shortcoming of existing rainfall-detecting approaches is the lack of a unified timeline to time-stamp the rainfall data returned by multiple devices. Fig. 1 shows a case in which three devices *without sharing a common clock* are used to detect ambient events. When event I occurs, three of them time-stamp event I with 22, 10, and 20, according to their own clock, respectively. Similarly they record the occurrence time of event II with 32, 20, and 30, respectively. In the analysis of the obtained data, event I and event II will be treated to happen at device 2 and device 3 simultaneously, even though event II happens a little late in comparison with event I. Even with a lot of multi-source data in hand, field experts still cannot precisely characterize the rainfall patterns if the data does not share a common clock; and sometimes, they will possibly achieve unconvincing or even wrong conclusions.

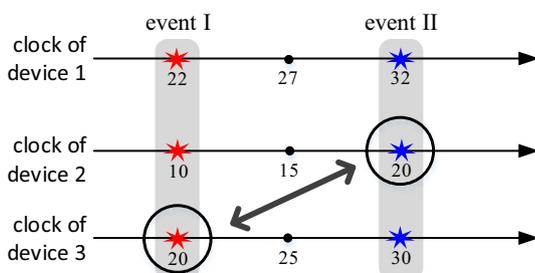


Fig. 1. Observations returned by three event-detecting devices without sharing a common clock.

To satisfy the urgent requirement for the real-time and time-synchronized rainfall monitoring in hydrology, this study presents a rainfall monitoring system, called RealRain, which takes the advantages of wireless sensor network (Shorey et al., 2006; Yick et al., 2008) and embedded computing. Each RealRain sensor mote can detect rainfall events once they occur—these events will invoke interrupts that can be captured by the RealRain mote; and through wireless links, RealRain can timely transport the time-synchronized rainfall data to users. In essential, RealRain is an event-driven wireless sensing framework. Since the RealRain mote is implemented based on the commercial wireless sensing platform, the RealRain system can acquisition other environmental parameters if external sensing devices, analog or digital, are attached to RealRain motes. With such an extension, end-users can deduce more powerful and accurate models that allow online analyses for micro-level environmental dynamics.

Specifically, the main contributions of this work are summarized as follows. (1) We introduce a commercial off-the-shelf (COTS) wireless platform as well as the according software such that RealRain can cost-effectively integrate with traditional rainfall-detecting (tipping bucket is used in this paper), monitor the rainfall events, and timely transmit the rainfall information without human interventions. (2) Aiming at achieving the large-scale, real-time, and reliable rainfall monitoring, we first design a tree-based policy of time synchronization which not only substantially reduces the message complexity but also enables all rainfall-detecting sensor nodes to share a globally identical clock; and then we propose a sample-send-store scheme to reliably collect rainfall information, even when challenging environments deteriorate the quality of wireless communication. (3) We build a proof-of-concept prototype of RealRain based on TinyOS programming environment and Telosb sensor mote (a popular COTS wireless sensing platform), both of which ensure an easily-deployed and function-rich platform for extension. We also conduct preliminary laboratory experiments to evaluate RealRain.

The rest of this paper includes the following parts. Section 2 introduces and analyzes some related work and gives the motivation of our study. Section 3 presents the overview, the objectives, and the designing details of the RealRain prototype. Section 4 gives in-depth discussions and some guidelines on implementing RealRain in the real world effectively and efficiently. We conduct preliminary experiments and show RealRain's performance in Section 5. Finally we conclude our study in Section 6.

## 2. Background and motivation

### 2.1. Related work

Early efforts on estimating rainfall often turn to the satellite imagery data (Barrett, 1993; Kidd and Barrett, 1990). Since such a method usually can give only macro-observations for offline analysis, it is unsuitable for environmental researches aiming at obtaining fine-grained and real-time rainfall measurements. Additionally the imagery data alone cannot produce accurate measurements at surface level. In the past a few years, therefore, a lot of attention has been given to design rainfall-detecting devices or apparatuses that can be deployed directly in the field to measure the *in situ* rainfall events. To monitor the city-scale rainfall, (Russo et al., 2005) uses the radar rainfall measurements and the rain gauge measurements together to improve the rainfall resolution. Crabit et al. (2011) propose a soft water level sensor to measure rainfall and stream flows and use a data logger to record the information of water level. They consider the energy consumption and the low-cost fabrication in designs. Duchon (2008) describes a rainfall-detection apparatus, which involves three vibrating-wire

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