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POWER OPTIMIZATION IN REMOTE MONITORING DEVICES

Abstract

System and method of environmental monitoring. In an embodiment, a remote monitoring device comprises power-consuming components comprising at least one sensor and a radio interface component, and a power source comprising a battery and a solar panel. The device stores mode information on operating modes defining differing levels of sensing capabilities and have different power consumption profiles. The device accumulates energy information regarding solar energy collected by the solar panel over a prior time period, obtains environmental information over a future time period, calculates estimated battery capacity data of the battery for the future time period based on the energy information and environmental information, calculates estimated operating times of the device when operating in the operating modes during the future time period based on the estimated battery capacity data and power consumption profiles, and selects between the operating modes during the future time period using the estimated operating times.

Inventors: KONTIO; Jari Pekka (Tampere, FI), TAIVALSAARI; Antero (Tampere, FI), AALTO; Antti (Sunnyvale, CA), VIITALA; Tomi (Tampere, FI)

Applicant: Nokia Solutions and Networks Oy (Espoo, FI)

Background/Summary

TECHNICAL FIELD

[0001] This disclosure is related to the field of environmental monitoring, and more particularly, to the operation of remote monitoring devices of an environmental monitoring system.

BACKGROUND

[0002] Environmental monitoring in general is a process of observing an environment to assess conditions. For example, environmental monitoring may be used for air quality, water sampling, soil quality, noise level, etc. Environmental monitoring may also be used to detect harmful events, such as wildfires or other natural disasters. Environmental monitoring systems may use a variety of tools or equipment depending on the use case.

[0003] For example, an environmental monitoring system may comprise a system of distributed monitoring or sensing devices that have wireless connectivity. One potential issue, however, is how to effectively operate these distributed monitoring devices in remote locations.

SUMMARY

[0004] Described herein is an environmental monitoring system comprising a plurality of remote monitoring devices configured for sensing (i.e., having one or more sensors) and wireless connectivity. In certain use cases, the remote monitoring devices are installed or placed at remote locations where solar power may be the sole source of power. Thus, the remote monitoring devices use an adaptive device controller that controls the behavior of a remote monitoring device to adjust or optimize energy consumption based on conditions experienced by the remote monitoring device. The adaptive device controller is able to adapt to the specific location/surrounding environment of a remote monitoring device, as well as environmental changes caused by seasonal variations. One technical benefit is that remote monitoring devices may operate in the remote locations for extended periods of time while providing an effective level of sensing capability. For example, the remote monitoring devices may be used for early detection of wildfires or other natural disasters. Another technical benefit is that remote monitoring devices are sensor-based, and provide a cost-effective option to image-based devices (e.g., camera, infrared, etc.) that have inherent limitations and higher power consumption profiles.

[0005] In an embodiment, a remote monitoring device comprises power-consuming components comprising at least one sensor, and a radio interface component configured for wireless connectivity. The remote monitoring device comprises a power source configured to provide power to the power-consuming components, where the power source comprises a battery, and at least one solar panel configured to charge the battery. The remote monitoring device comprises at least one processor, and at least one memory configured to store mode information on a plurality of operating modes defining differing levels of sensing capabilities by the at least one sensor, where the operating modes have different power consumption profiles. The memory further stores instructions that, when executed by the at least one processor, cause the remote monitoring device at least to accumulate energy information regarding solar energy collected by the at least one solar panel over a prior time period, obtain environmental information regarding a location of the remote monitoring device over a future time period, calculate estimated battery capacity data of the battery for the future time period based on the energy information and the environmental information, calculate estimated operating times of the remote monitoring device when operating in the operating modes during the future time period based on the estimated battery capacity data and the power consumption profiles, and select between the operating modes during the future time period

using the estimated operating times.

[0006] In an embodiment, a method of environmental monitoring in a remote monitoring device is disclosed. The remote monitoring device comprises power-consuming components and a power source configured to provide power to the power-consuming components, where the power-consuming components comprise at least one sensor and a radio interface component configured for wireless connectivity, and the power source comprises a battery and at least one solar panel configured to charge the battery. The method comprises storing mode information on a plurality of operating modes defining differing levels of sensing capabilities by the at least one sensor, wherein the operating modes have different power consumption profiles, accumulating energy information regarding solar energy collected by the at least one solar panel over a prior time period, obtaining environmental information regarding a location of the remote monitoring device over a future time period, calculating estimated battery capacity data of the battery for the future time period based on the energy information and the environmental information, calculating estimated operating times of the remote monitoring device when operating in the operating modes during the future time period based on the estimated battery capacity data and the power consumption profiles, and selecting between the operating modes during the future time period using the estimated operating times.

[0007] Other embodiments may include computer readable media, other systems, or other methods as described below.

[0008] The above summary provides a basic understanding of some aspects of the specification. This summary is not an extensive overview of the specification. It is intended to neither identify key or critical elements of the specification nor delineate any scope of the particular embodiments of the specification, or any scope of the claims. Its sole purpose is to present some concepts of the specification in a simplified form as a prelude to the more detailed description that is presented later.

Description

DESCRIPTION OF THE DRAWINGS

[0009] Some embodiments of the invention are now described, by way of example only, and with reference to the accompanying drawings. The same reference number represents the same element or the same type of element on all drawings.

[0010] FIG. **1** is a block diagram illustrating an environmental monitoring system in an illustrative embodiment.

[0011] FIG. **2** illustrates communication of a remote monitoring device with a central controller in an illustrative embodiment.

[0012] FIG. **3** is a block diagram illustrating a remote monitoring device in an illustrative embodiment.

[0013] FIG. **4** illustrates a set of sensors implemented in a remote monitoring device in an illustrative embodiment.

[0014] FIG. **5** is a flow chart illustrating a method of performing environmental monitoring in an illustrative embodiment.

[0015] FIG. **6** illustrates mode information for a remote monitoring device in an illustrative embodiment.

[0016] FIG. **7** is a block diagram illustrating a device controller in operation in an illustrative embodiment.

[0017] FIG. **8** is a histogram representing energy information in an illustrative embodiment.

[0018] FIG. **9** is a graph illustrating a cloud cover forecast in an illustrative embodiment.

[0019] FIG. **10** is a graph illustrating cloud estimates in an illustrative embodiment.

[0020] FIG. **11** is a graph illustrating estimated battery capacity data in an illustrative embodiment.

[0021] FIG. **12** is a block diagram of a mode selector in an illustrative embodiment. FIG. **13** is a flow chart illustrating a method of utilizing a Machine Learning (ML) system to select between operating modes in an illustrative embodiment.

[0022] FIG. **14** is a flow chart illustrating additional steps of the method in FIG. **5** in an illustrative embodiment.

[0023] FIG. **15** is a perspective view of a remote monitoring device in an illustrative embodiment.

[0024] FIG. **16** is a perspective view of a remote monitoring device mounted on a tripod in an illustrative embodiment.

[0025] FIG. **17** illustrates a plurality of remote monitoring devices deployed in a forest in an illustrative embodiment.

DESCRIPTION OF EMBODIMENTS

[0026] The figures and the following description illustrate specific exemplary embodiments. It will thus be appreciated that those skilled in the art will be able to devise various arrangements that, although not explicitly described or shown herein, embody the principles of the embodiments and are included within the scope of the embodiments. Furthermore, any examples described herein are intended to aid in understanding the principles of the embodiments, and are to be construed as being without limitation to such specifically recited examples and conditions. As a result, the inventive concept(s) is not limited to the specific embodiments or examples described below, but by the claims and their equivalents.

[0027] FIG. **1** is a block diagram illustrating an environmental monitoring system **100** in an illustrative embodiment. Environmental monitoring system **100** (also referred to as an environmental monitoring architecture) comprises a network of distributed devices configured to monitor a physical environment. In an embodiment, environmental monitoring system **100** comprises a plurality of remote monitoring devices **102** (RMD) that are deployed or installed at locations **106** (e.g., terrestrial locations on Earth). A remote monitoring device **102** is a type of device embedded with hardware, such as sensors, processors, etc., configured to perform sensing or detection functions/operations and configured for wireless connectivity. Environmental monitoring system **100** may also be referred to as an Internet of Things (IoT) network **101**, and remote monitoring devices **102** may be referred to as IoT devices **108**.

[0028] In an embodiment, environmental monitoring system **100** further comprises a central controller **120**. Central controller **120** comprises a server, hub, system, etc., providing a centralized point for managing the remote monitoring devices **102**. Central controller **120** may be implemented on a cloud-computing platform **122**, on a hardware platform, on a combination of a cloud-computing platform **122** and a hardware platform, etc. Central controller **120** may send data or instructions/commands to the remote monitoring devices **102**, may receive and/or analyze data reported by the remote monitoring devices **102**, and/or perform other functions. While central controller **120** may be part of environmental monitoring system **100**, remote monitoring devices **102** may be configured to operate generally independent from central controller **120** in some embodiments.

[0029] Remote monitoring devices **102** are equipped with sensing technology to collect data, and therefore may be referred to as sensor-based. For example, remote monitoring devices **102** (also referred to as remote environmental monitoring devices) may be equipped with one or more sensors configured to detect or measure environmental conditions. Remote monitoring devices **102** are also equipped with wireless connectivity or communication technology to transmit data over a communication network, such as to central controller **120**, and/or to receive data over the communication network. In an embodiment, remote monitoring devices **102** are configured to communicate with central controller **120** (and possibly with each other) via radio or wireless links **104**.

[0030] FIG. **2** illustrates communication of a remote monitoring device **102** with central controller **120** in an illustrative embodiment. From its location **106**, a remote monitoring device **102** may

communicate with central controller **120** via a Terrestrial Network (TN) **210**, such as a cellular network **212** comprising one or more base stations **214**. However, other types of terrestrial communications are considered herein, such as WiFi, Bluetooth, long range wide area network (LoRaWAN), etc. In an embodiment, remote monitoring device **102** may communicate with central controller **120** via a Non-Terrestrial Network (NTN) **220**, illustrated with an NTN satellite **222**. NTNs are networks, or segments of networks, using an airborne or space-borne vehicle to embark a transmission equipment relay node or base station.

[0031] Environmental monitoring system **100** as shown in FIG. **1** may be used as an early warning system, such as for natural disasters (e.g., wildfires/forest fires), health emergencies, and/or other types of situations.

[0032] FIG. **3** is a block diagram illustrating a remote monitoring device **102** in an illustrative embodiment. Remote monitoring device **102** includes a device terminal **301** and one or more solar panels **356**. Device terminal **301** includes a housing **302**, which is a protective enclosure (e.g., weatherproof, waterproof, etc.) configured to protect internal equipment. Within housing **302**, remote monitoring device **102** comprises a plurality of power-consuming components **304**. A power-consuming component **304** is a type of hardware component or equipment that uses electrical power to operate. Power-consuming components **304** include a radio interface component **320**, which is a hardware component or means that represents the local radio resources of the remote monitoring device **102** configured for wireless connectivity. In an embodiment, radio interface component **320** may comprise a Radio Frequency (RF) unit **322** (e.g., one or more radio transceivers (TRX) **324**) and one or more antennas **326**. RF unit **322** may be configured for 5G New Radio (NR), Long Term Evolution (LTE), WiFi, Bluetooth, LoRaWAN, etc. Power-consuming components **304** further include one or more sensors **330** (e.g., sensor **330-1**, **330-2**, . . . , **330-6**). A sensor **330** is a device that detects or measures input from a physical environment, and outputs measurement data. Remote monitoring device **102** may include other power-consuming components **304** not specifically shown in FIG. **3** that are disposed within housing **302**.

[0033] Device terminal **301** further comprises one or more processors **306** and a memory **308** disposed within housing **302**. Processor **306** represents the internal circuitry, logic, hardware, means, etc., that provides functions of remote monitoring device **102**. For example, processor **306** may execute a device controller **340** (also referred to as an adaptive device controller), which comprises a component or means for managing or controlling operations performed by remote monitoring device **102**. Processor **306** may comprise microprocessor, a set of one or more processors, a multi-processor core, etc., depending on the particular implementation. Processor **306** may be configured to execute instructions **342** for software that are loaded into memory **308**. Memory **308** is a non-transitory computer readable storage medium for data, instructions, applications, etc., and is accessible by processor **306**. Memory **308** is a hardware storage device capable of storing information on a temporary basis and/or a permanent basis. Memory **308** may comprise a random-access memory, or any other volatile or non-volatile storage device. It is noted that processor **306** and/or memory **308** may also be considered a type of power-consuming component **304**.

[0034] In an embodiment, remote monitoring device **102** may be deployed in remote locations where there is no reasonable access to an electrical grid. Thus, the power source **352** of remote monitoring device **102** comprises one or more batteries **354**, and one or more solar panels **356**. Solar panel **356** is configured to generate solar energy **358** by converting sunlight into electrical energy. The solar energy **358** generated by the solar panel **356** is used to charge the battery **354**, and power the power-consuming components **304**.

[0035] Remote monitoring device **102** may comprise various other components not specifically illustrated in FIG. **3**.

[0036] Remote monitoring devices **102** may include a comprehensive set of detection or sensing capabilities depending on the application. FIG. **4** illustrates a set of sensors **330** implemented in a

remote monitoring device **102** in an illustrative embodiment. Sensors **330** may comprise a carbon dioxide (CO_2) sensor **402** configured to measure the concentration of carbon dioxide in the surrounding environment. Sensors **330** may comprise a carbon monoxide (CO) sensor **404** configured to measure the concentration of carbon monoxide in the surrounding environment. Sensors **330** may comprise a Volatile Organic Compound (VOC) sensor **406** configured to detect or measure off-gasses produced by various volatile organic compounds in the surrounding environment. Sensors **330** may comprise a particulate matter sensor **408** configured to detect or measure the quantity and/or concentration of dust particles in the surrounding environment. Sensors **330** may comprise a gas sensor **410** configured to detect or measure the concentration of various gases in the surrounding environment. Sensors **330** may comprise a temperature sensor **412** configured to measure the temperature in the surrounding environment. Sensors **330** may include a programmable sensor **414** having various gas composition recognition capabilities. The programmable sensor **414** may use onboard artificial intelligence (AI) or machine learning (ML) capabilities that are trained to detect various gas compositions, as well as ambient temperature, humidity, air pressure, general air quality measurements, etc. Sensors **330** may include a 3-axis accelerometer **416**. Sensors **330** may include a current sensor **418** configured to measure charging current **360** generated by the solar panel(s) **356** (see FIG. **3**) and used to charge the battery **354**. The output from one or more of the sensors **330** comprise sensor measurements **420**.

[0037] FIG. **4** provides an example of the types of sensors **330** that may be implemented in a remote monitoring device **102**. However, the number and types of sensors **330** implemented in a remote monitoring device **102** may vary depending on the application or use case of the remote monitoring device **102**.

[0038] In an embodiment, remote monitoring devices **102** may be intended for long-term use in remote locations **106** where there is typically no energy source available other than solar power. The amount of available solar energy **358** can vary considerably based on time of day, time of year, and overall device placement (e.g., remote monitoring devices **102** mounted on the ground, high up on a tree or pole, etc.). Factors such as tree canopy, other nearby vegetation, and/or fixed structures in the vicinity of each remote monitoring device **102** can also have a significant impact on available solar energy **358**. Thus, the amount of available solar energy **358** can vary significantly from one remote monitoring device **102** to another based on their deployment location **106**.

[0039] One factor for the overall success of a remote monitoring solution is the optimization of energy consumption in the remote monitoring devices **102**. In an ideal scenario, remote monitoring devices **102** would run all sensors **330** in the fastest possible contiguous measurement mode in order to maximize detection. In practice however, it is not realistic to run all sensors **330** in the fastest possible measurement mode continuously because the amount of energy required by individual sensors **330** can vary considerably. Thus, the device controller **340** in the individual remote monitoring devices **102** adapts to conditions at the deployment location **106** to balance power consumption with sensing capabilities.

[0040] FIG. **5** is a flow chart illustrating a method **500** of performing environmental monitoring in an illustrative embodiment. The steps of method **500** will be described with reference to remote monitoring device **102** in FIG. **3**, but those skilled in the art will appreciate that method **500** may be performed in other systems or devices. Also, the steps of the flow charts described herein are not all inclusive and may include other steps not shown, and the steps may be performed in an alternative order.

[0041] Remote monitoring device **102** stores mode information **344** on a plurality of operating modes for remote monitoring device **102** (step **502**), such as in memory **308**. An operating mode specifies a configuration of a remote monitoring device **102** characterized by the active functions performed. FIG. **6** illustrates mode information **344** for a remote monitoring device **102** in an illustrative embodiment. Mode information **344** defines or specifies multiple operating modes **600** (e.g., mode **600-1**, **600-2**, . . . , **600-5**) that are predefined for a remote monitoring device **102**. In an

embodiment, the different operating modes **600** define differing levels of sensing capabilities by the sensor(s) **330**. For example, mode **600-1** may represent a "hibernation" mode where each sensor **330** is "off" or deactivated. Mode **600-2** may represent a "standby" mode where sensor **330-3** is activated with a sampling rate of fifteen minutes, while other sensors **330** are "off" or deactivated. Mode **600-3** may represent a "normal" mode where sensors **330-2** thru **330-5** are activated with various sampling rates, while other sensors **330** are "off" or deactivated. Modes **600-4** and **600-5** may represent an "alert" mode and "emergency" mode, respectively, where each of the sensors **330** are activated with various sampling rates.

[0042] The overall energy consumption of remote monitoring device **102** can vary significantly depending on the operating mode **600**. Thus, the mode information **344** may further define or specify a power consumption profile **606** for each operating mode **600**. The power consumption profile **606** is an estimate or indication of the power consumed by power-consuming components **304** when operating in an operating mode **600**. For example, the power consumption profiles **606** may be predefined based on an average measurement (e.g., a one-hour average) in similar remote monitoring devices **102**. Also, device controller **340** may build or adjust the power consumption profiles **606** over time based on actual power consumption measurements or estimates. FIG. **6** illustrates some example power consumption values (e.g., ˜20 µA, ˜1 mA, ˜67 mA, etc.) for the different operating modes **600** to illustrate that the operating modes **600** have different power consumption profiles **606**.

[0043] In FIG. **5**, device controller **340** of remote monitoring device **102** collects or accumulates energy information regarding solar energy **358** collected by the solar panel **356** over a prior time period (step **504**). FIG. **7** is a block diagram illustrating device controller **340** in operation in an illustrative embodiment. Device controller **340** accumulates energy information **702** over a number (n) of past or prior days, such as seven days, fourteen days, twenty-one days, etc. To accumulate the energy information **702**, device controller **340** may receive measurement data from a current sensor **418** indicating the actual charging current **360** (mA) provided by solar panel **356** to charge the battery **354**. Device controller **340** may receive the measurement data periodically (e.g., hourly) over a number (n) of past days.

[0044] In an embodiment, device controller **340** may build a histogram representing the energy information **702** (optional step **514** of FIG. **5**). FIG. **8** is a histogram **801** representing the energy information **702** in an illustrative embodiment. In an embodiment, histogram **801** indicates a moving average **808** of charging current **360** measured at the solar panel **356** for each time increment (e.g., hourly) over a number of past days. The horizontal axis in FIG. **8** represents the time increments **802** (e.g., hours), and the vertical axis represents charging current values **804**. Device controller **340** may incrementally build histogram **801** (e.g., a graph comprising twenty-four segments representing available solar energy **358** at each hour of the day) based on the actual charging current **360** provided by solar panel **356**. Because histogram **801** is based on the actual measured charging current **360**, the histogram **801** reflects solar energy accumulation during a day, and automatically takes into account trees, vegetation, structures, etc., that may be blocking available sunlight around remote monitoring device **102** at certain times (hours) during the day. Histogram **801** is therefore specific to remote monitoring device **102** and the location **106** of the remote monitoring device **102**. A moving average **808** over a number of past days for each time increment **802** may be used to average out significant daily variations in the available sunlight. One technical benefit is the histogram **801** represents a typical daily energy accumulation profile instead of being impacted by individual extremely sunny, cloudy, or rainy days. The charging current values **804** in histogram **801** may be represented as percentages **806** of the maximum possible charging current of the solar panel **356**. Alternatively, charging current values **804** may be values between "0" and "1" (representing a multiplier against the maximum possible charging current), or another representation of charging current.

[0045] In FIG. **5**, device controller **340** performs or triggers a mode selection process (step **505**).

The trigger for the mode selection process may vary as desired. For example, the mode selection process may be triggered upon expiration of a predefined time period. In another example, a condition or event may trigger the mode selection process, such as sensor measurements **420** (e.g., elevated concentration of gas or particulates in the surrounding environment, concentration of gas or particulates dropping below a threshold, etc.), an alert from an external server or neighboring remote monitoring device **102**, a State of Charge (SoC) of the battery **354**, etc.

[0046] For the mode selection process, device controller **340** obtains environmental information regarding the location **106** of remote monitoring device **102** over a future time period (step **506**). As illustrated in FIG. **7**, device controller **340** obtains environmental information **704** for the next or future number (m) of hours, such as twelve hours, twenty-four hours, forty-eight hours, etc. Device controller **340** may access an external server **750** (e.g., central controller **120**, a server providing a weather service (e.g., National Oceanic and Atmospheric Administration (NOAA)), etc.) through radio interface component **320** to obtain the environmental information **704**. In an embodiment, the environmental information **704** may comprise a weather forecast **706** for the location **106** of remote monitoring device **102** over the future time period (optional step **516** of FIG. **5**). The weather forecast **706** may comprise a sunshine forecast, a cloudiness forecast, a cloud cover forecast, etc. For example, device controller **340** may query a weather service using the location **106** (e.g., Global Positioning System (GPS) coordinates) of remote monitoring device **102** as an input parameter.

[0047] FIG. **9** is a graph illustrating a cloud cover forecast **901** in an illustrative embodiment. The horizontal axis in FIG. **9** represents the time increments **902** (e.g., hours in a day), and the vertical axis represents a percentage of cloud cover **904**. Based on the weather forecast **706** (e.g., cloud cover forecast **901**), device controller **340** may generate sun or cloud estimates **708** (see FIG. **7**) for a future number of time increments (e.g., hours) at the location **106** of the remote monitoring device **102**. FIG. **10** is a graph illustrating cloud estimates **708** in an illustrative embodiment. The horizontal axis in FIG. **10** represents the time increments **1002** (e.g., hours in a day), and the vertical axis represents cloud estimate values **1004**. For example, the cloud estimate values **1004** may have a value of "1" for a sunny forecast, a value of "0.7" for a partly cloudy forecast, a value of "0.3" for a cloudy forecast, and a value of "0" for a precipitation forecast. These values are provided as examples, as the cloud estimates **708** may have other desired values. Further, device controller **340** may avoid generating cloud estimates **708** for nighttime hours since the amount of solar energy **358** harvested at nighttime is close to zero. One technical benefit is a weather forecast **706** (e.g., a cloud cover forecast **901**) indicates how solar energy collection may be affected in the future.

[0048] In FIG. **5**, device controller **340** calculates estimated battery capacity data of the battery **354** for the future time period based on the energy information **702** and the environmental information **704** (step **508**). As illustrated in FIG. **7**, device controller **340** calculates the estimated battery capacity data **710** for a future number (m) of time increments (e.g., hours) based on the energy information **702** and the environmental information **704**. For example, device controller **340** may use the histogram **801** indicating the moving average **808** of charging current **360** measured at the solar panel **356** over a number of past days, and the environmental information **704** (e.g., weather forecast **706**) for the future number (m) of hours to calculate the estimated battery capacity data **710**.

[0049] The environmental information **704** may therefore comprise an adjustment factor to the moving average **808** of charging current **360** in time increments based on the weather forecast **706**. FIG. **11** is a graph illustrating estimated battery capacity data **710** in an illustrative embodiment. The horizontal axis in FIG. **11** represents the time increments **1102** (e.g., hours in a day), and the vertical axis represents estimated battery capacity values **1104**. For example, estimated battery capacity values **1104** may be represented as percentages **1106** of the maximum battery capacity (e.g., ampere hours (Ah)) of battery **354**. Device controller **340** may therefore combine the

averaged solar energy accumulation histogram **801** with the hourly cloud estimates **708** (e.g., multiplication factors) to generate hourly estimated battery capacity data **710**.

[0050] In FIG. **5**, device controller **340** calculates estimated operating times of remote monitoring device **102** when operating in one or more of the operating modes **600** during the future time period based on the estimated battery capacity data **710** and the power consumption profiles **606** (step **510**). As illustrated in FIG. **7**, device controller **340** may calculate estimated operating times **712** of remote monitoring device **102** for each of the operating modes **600**. As described above, each operating mode **600** has a different power consumption profile **606**. Thus, device controller **340** calculates an estimated operating time **712** for an operating mode **600** during the future time period based on the estimated battery capacity data **710** and the power consumption profile **606** for the operating mode **600**. Device controller **340** may calculate the estimated operating times **712** on an hourly basis, a daily basis, and/or some other time interval.

[0051] Although the power consumption profiles **606** may provide estimated power consumption for remote monitoring device **102** in the operating modes **600**, other factors may impact the actual power consumption in the operating modes **600**. Thus, device controller **340** may adjust the estimated operating times **712** based on one or more other factors (optional step **518** of FIG. **5**). For example, signal strength of radio interface component **320** may impact the actual power consumption. Thus, device controller **340** may adjust the estimated operating times **712** based on signal strength. Device controller **340** may also measure actual power consumption in one or more of the operating modes **600** over time, and adjust the estimated operating times **712** based on actual power consumption measurements. One technical benefit is device controller **340** may fine-tune the estimated operating times **712** to improve accuracy.

[0052] In FIG. **5**, device controller **340** selects between the operating modes **600** during the future time period using the estimated operating times **712** (step **512**). As illustrated in FIG. **7**, device controller **340** may implement a mode selector **720** that selects between the operating modes **600** based on the estimated operating times **712**. Mode selector **720** may use a variety of other information to select an operating mode **600** in addition to the estimated operating times **712**. For example, mode selector **720** may use energy information **702**, environmental information **704**, sensor measurements **420**, and/or other information as input parameters when selecting an operating mode **600**. Mode selector **720** may be programmed with a selection algorithm that uses a set of thresholds and the input parameters (e.g., estimated operating times **712**, energy information **702**, environmental information **704**, sensor measurements **420**, etc.) to select an operating mode **600**.

[0053] In an embodiment, mode selector **720** may implement or utilize a machine learning (ML) system to select between the operating modes **600** (optional step **520**). FIG. **12** is a block diagram of a mode selector **720** in an illustrative embodiment. In an embodiment, mode selector **720** comprises an ML system **1202**. In general, Artificial Intelligence (AI) is the simulation of human intelligence processes by machines, especially computer systems. Machine learning (ML) is a type of AI involving the use and development of computer systems that are able to learn and adapt without following explicit instructions, by using algorithms and statistical models to analyze and draw inferences from patterns in data. ML system **1202** may comprise circuitry, logic, hardware, software, means, etc., configured to use machine learning techniques to perform functions described for mode selector **720** and/or device controller **340**. ML system **1202** may comprise an ML algorithm **1204**, which is a procedure that is run on data to create an ML model **1206**. For example, ML algorithm **1204** may perform pattern recognition on a dataset to learn from the dataset and generate ML model **1206**. ML model **1206** is the output of the ML algorithm **1204**, and comprises the model data and associated procedures/algorithms for making predictions or recommendations based on the model data. One technical benefit is ML system **1202** is configured to learn from data collected by remote monitoring device **102** to optimize the behavior of remote monitoring device **102** over time.

[0054] FIG. **13** is a flow chart illustrating a method **1300** of utilizing a ML system **1202** to select between operating modes **600** in an illustrative embodiment. ML system **1202** runs ML algorithm **1204** on a dataset to train ML model **1206** (step **1302**). In an embodiment, ML algorithm **1204** may comprise an unsupervised learning algorithm, and the dataset may comprise historical data collected by remote monitoring device **102**. ML system **1202** may retrain ML model **1206** on occasion, such as based on an updated dataset, model updates provided by central controller **120**, etc.

[0055] In an embodiment, ML model **1206** (as trained) is configured to balance maximum sensing capabilities **1230** of the sensor(s) **330** with maximum operating time **1232** of the remote monitoring device **102** in selecting between the operating modes **600** (see also, FIG. **12**). For example, a goal for the ML algorithm **1204** is to try to learn and reach an optimal balance between maximum sensing capabilities **1230** while allowing the remote monitoring device **102** to operate as long as possible even when new solar energy **358** is unavailable for a time period. The sensing capabilities refers to the number of sensors **330** activated and/or sampling rate of the sensors **330** in a remote monitoring device **102**. Thus, the maximum sensing capabilities **1230** (also referred to as maximum detection readiness) may refer to a remote monitoring device **102** operating in the highest possible operating mode **600** with as many sensors **330** running contiguously as possible. Operating time **1232** refers to the amount of time that power-consuming components **304** are active or operating.

[0056] ML system **1202** then utilizes the ML model **1206** (as trained) to select operating modes **600** for remote monitoring device **102** (step **1304**). To do so, ML system **1202** applies input parameters **1210** to ML model **1206** (step **1306**). ML system **1202** may apply a variety of input parameters **1210** to the ML model **1206** when selecting an operating mode **600** for a particular time period (see FIG. **12**). ML system **1202** may apply the estimated operating times **712** as an input parameter **1210** to the ML model **1206** (optional step **1310**), as discussed above. ML system **1202** may apply energy information **702** (e.g., histograms **801**) as an input parameter **1210** to the ML model **1206** (optional step **1312**). Energy accumulation patterns might look different during different times/seasons of the year as obstacles (e.g., tree canopy) surrounding remote monitoring device **102** may block sunlight at different times when the sun is at higher or lower elevations in the sky. For example, energy information **702** accumulated over time may indicate that late fall and winter seasons result in lower amounts of solar energy **358**, and it may be beneficial for the ML system **1202** to optimize remote monitoring device **102** towards maximum operating time **1232** during these seasons.

[0057] ML system **1202** may apply environmental information **704** as an input parameter **1210** to the ML model **1206** (optional step **1314**). For example, if it is known that the next hours/days will be cloudy or rainy (i.e., little or no solar energy available), it may be beneficial for the ML system **1202** to optimize remote monitoring device **102** towards maximum operating time **1232**. Conversely, if the next hours/days are known to be sunny (i.e., adequate solar power available), it may be beneficial for the ML system **1202** to optimize remote monitoring device **102** towards maximum sensing capability **1230**. In another example, winter season, times of heavy rain/snow, and/or other conditions may represent minimal danger of wildfires, and it may be beneficial for the ML system **1202** to keep remote monitoring device **102** in the lowest operating mode **600** (e.g., hibernation mode) with as few sensors **330** running as possible in order to minimize energy consumption.

[0058] ML system **1202** may apply sensor measurements **420** as an input parameter **1210** to the ML model **1206** (optional step **1316**). For example, when a sensor **330** detects a concentration of gas or particles in the surrounding environment that is above a threshold, it may be beneficial for the ML system **1202** to optimize remote monitoring device **102** towards maximum sensing capability **1230** (e.g., choosing an operating mode **600** that uses a broader variety of sensors **330** with faster sampling and data upload rates). ML system **1202** may apply external warning data **1222** or other external information as an input parameter **1210** to the ML model **1206** (optional step **1318**). For

example, wildfire warnings or the like may be available from external weather services or emergency services that may be used as an input parameter **1210**.

[0059] ML system **1202** may apply other input parameters **1210** as desired. Based on the input parameters **1210** applied, the ML model **1206** outputs a selected operating mode **600** for remote monitoring device **102** (step **1308**). As shown in FIG. **12**, ML model **1206** generates output **1212** in the form of a mode selection **1214** for a configurable time period (e.g., one hour, six hours, twelve hours, twenty-four hours, etc.). One technical benefit is ML system **1202** is capable of independently and autonomously adapting to present conditions when selecting an optimal operating mode **600** for remote monitoring device **102**.

[0060] ML system **1202** as shown in FIG. **12** may be implemented on-board remote monitoring device **102**. In another embodiment, ML system **1202** may be implemented on an external device. For example, central controller **120** has more processing and storage resources than a remote monitoring device **102**. Thus, central controller **120** may train the ML model **1206** based on historical data received from the remote monitoring device **102** over time, and provide the trained ML model **1206** to remote monitoring device **102**. In another example, central controller **120** may utilize the ML model **1206** to provide updated thresholds or other data used by the selection algorithm in remote monitoring device **102**.

[0061] FIG. **14** is a flow chart illustrating additional steps of method **500** in an illustrative embodiment. After selecting the operating mode **600** for remote monitoring device **102**, device controller **340** controls operation of remote monitoring device **102** in the selected operating mode **600** for a time period (step **1422**), such as one hour, six hours, twelve hours, twenty-four hours, or some other time interval. Device controller **340** may send data (e.g., sensor measurements **420**, alarm or alert signals, etc.) to an external device via radio interface component **320** (step **1424**) during or after operation in the selected operating mode **600**. For example, device controller **340** may report or upload sensor measurements **420** or other data to central controller **120**, may receive instructions or commands from central controller **120**, etc. In another example, device controller **340** may send data to a configurable address or destination (other than central controller **120**), such as sending an alert signal to the nearest fire brigade or law enforcement, sending data to a neighboring remote monitoring device **102**, etc.

[0062] To enable deployment of remote monitoring device **102** in a truly remote location, the remote monitoring device **102** may include a Message Queuing Telemetry Transport (MQTT) command interface. MQTT is a messaging protocol for low-bandwidth and high-latency devices. Through the MQTT command interface, central controller **120** may control individual sensors **330** of remote monitoring device **102** (e.g., activation/deactivation, sampling rates, etc.), may control data upload rates, optimize radio connectivity, etc. Central controller **120** may remotely control the remote monitoring device **102** (e.g., from the cloud) without requiring personnel to physically visit the location **106** of the remote monitoring device **102**. However, it may be beneficial for the remote monitoring device **102** to behave as autonomously as possible.

[0063] When another trigger is detected, method **500** may return to step **506** in FIG. **5** to perform the mode selection process. One technical benefit of method **500** is remote monitoring devices **102** can effectively strike a balance between energy consumption and sensing capability, which allows the remote monitoring devices **102** to operate long-term in remote locations **106** where no energy source is available other than solar energy **358**.

Example

[0064] In the following example, additional processes, systems, and methods may be described in the context of environmental monitoring. The processes, systems, and methods described in this example may be incorporated in embodiments described above as desired.

[0065] An example use case of remote monitoring devices **102** may be for an early warning system for wildfires/forest fires. Wildfires are some of the most destructive natural disasters in the world. Solar-powered remote monitoring devices **102** as described above may be deployed at remote

locations to monitor for early signs of a wildfire. FIG. **15** is a perspective view of a remote monitoring device **102** in an illustrative embodiment. Remote monitoring device **102** includes a device terminal **301** and a solar panel **356**. Device terminal **301** includes a housing **302** that houses sensitive internal equipment, such as sensors **330**, processor **306**, memory **308**, radio interface component **320** (illustrated by antenna **326**), etc. FIG. **16** is a perspective view of a remote monitoring device **102** mounted on a tripod **1612** in an illustrative embodiment. Device terminal **301** and solar panel **356** may be mounted on a pole **1610** of tripod **1612** as shown in FIG. **16**. The assembly of the tripod **1612** and remote monitoring devices **102** may be deployed at a remote location **106**. Although a tripod **1612** is shown, it is understood that a remote monitoring device **102** may be deployed or mounted in other ways, such as to a tree, a power pole, a building, etc. FIG. **17** illustrates a plurality of remote monitoring devices **102** deployed in a forest in an illustrative embodiment. Remote monitoring devices **102** may be deployed at strategic locations in or around the forest to provide early detection of a wildfire.

[0066] Other early warning systems may use image-based detection, such as camera-based, video-based, or satellite-based. However, these types of early warning systems have drawbacks related to their ability to perform fire detection early enough. Also, weather conditions such as heavy clouds, pollen, dust, or other airborne pollution can also reduce the effectiveness of these systems (especially for satellite-based systems). In addition, energy consumption of image-based systems can be excessive for deployment in remote locations where detection equipment will have to operate on solar power alone for months or possibly years without maintenance. The sensor-based system of remote monitoring devices **102** as described herein provide a cost-effective option for detection of wildfires, especially in their early, smoldering phases where potential savings are the greatest. The remote monitoring devices **102** as described herein are able to operate effectively via solar power by switching between the different operating modes **600** as discussed above.

[0067] Any of the various elements or modules shown in the figures or described herein may be implemented as hardware, software, firmware, or some combination of these. For example, an element may be implemented as dedicated hardware. Dedicated hardware elements may be referred to as "processors", "controllers", or some similar terminology. When provided by a processor, the functions may be provided by a single dedicated processor, by a single shared processor, or by a plurality of individual processors, some of which may be shared. Moreover, explicit use of the term "processor" or "controller" should not be construed to refer exclusively to hardware capable of executing software, and may implicitly include, without limitation, digital signal processor (DSP) hardware, a network processor, application specific integrated circuit (ASIC) or other circuitry, field programmable gate array (FPGA), read only memory (ROM) for storing software, random access memory (RAM), non-volatile storage, logic, or some other physical hardware component or module.

[0068] Also, an element may be implemented as instructions executable by a processor or a computer to perform the functions of the element. Some examples of instructions are software, program code, and firmware. The instructions are operational when executed by the processor to direct the processor to perform the functions of the element. The instructions may be stored on storage devices that are readable by the processor. Some examples of the storage devices are digital or solid-state memories, magnetic storage media such as a magnetic disks and magnetic tapes, hard drives, or optically readable digital data storage media.

[0069] As used in this application, the term "circuitry" may refer to one or more or all of the following: [0070] (a) hardware-only circuit implementations (such as implementations in only analog and/or digital circuitry); [0071] (b) combinations of hardware circuits and software, such as (as applicable): [0072] (i) a combination of analog and/or digital hardware circuit(s) with software/firmware; and [0073] (ii) any portions of hardware processor(s) with software (including digital signal processor(s)), software, and memory(ies) that work together to cause an apparatus, such as a mobile phone or server, to perform various functions); and [0074] (c) hardware circuit(s)

and or processor(s), such as a microprocessor(s) or a portion of a microprocessor(s), that requires software (e.g., firmware) for operation, but the software may not be present when it is not needed for operation.

[0075] This definition of circuitry applies to all uses of this term in this application, including in any claims. As a further example, as used in this application, the term circuitry also covers an implementation of merely a hardware circuit or processor (or multiple processors) or portion of a hardware circuit or processor and its (or their) accompanying software and/or firmware. The term circuitry also covers, for example and if applicable to the particular claim element, a baseband integrated circuit or processor integrated circuit for a mobile device or a similar integrated circuit in server, a cellular network device, or other computing or network device.

[0076] Although specific embodiments were described herein, the scope of the disclosure is not limited to those specific embodiments. The scope of the disclosure is defined by the following claims and any equivalents thereof.

Claims

1. A remote monitoring device (**102**), comprising: power-consuming components (**304**) comprising at least one sensor (**330**), and a radio interface component (**320**) configured for wireless connectivity; a power source (**352**) configured to provide power to the power-consuming components, wherein the power source comprises a battery (**354**), and at least one solar panel (**356**) configured to charge the battery; at least one processor (**306**); and at least one memory (**308**) configured to store mode information (**344**) on a plurality of operating modes (**600**) defining differing levels of sensing capabilities by the at least one sensor, wherein the operating modes have different power consumption profiles (**606**); the at least one memory further storing instructions (**342**) that, when executed by the at least one processor, cause the remote monitoring device at least to accumulate energy information (**702**) regarding solar energy (**358**) collected by the at least one solar panel over a prior time period; the remote monitoring device characterized in that the at least one processor further causes the remote monitoring device at least to: trigger a mode selection process within the remote monitoring device to: obtain environmental information (**704**) regarding a location of the remote monitoring device over a future time period; calculate estimated battery capacity data (**710**) of the battery for the future time period based on the energy information and the environmental information; calculate estimated operating times (**712**) of the remote monitoring device when operating in the operating modes during the future time period based on the estimated battery capacity data and the power consumption profiles; and select between the operating modes during the future time period using the estimated operating times, wherein the mode selection process is triggered within the remote monitoring device based on sensor measurements (**420**) from the at least one sensor.

2. The remote monitoring device of claim 1, wherein the at least one processor further causes the remote monitoring device at least to: build an hourly histogram (**801**) regarding the energy information indicating a moving average (**808**) of charging current (**360**) measured at the at least one solar panel for each hour over a number of prior days.

3. The remote monitoring device of claim 1, wherein: the mode selection process is triggered within the remote monitoring device based on an elevated concentration of gas or particulates in the sensor measurements from the at least one sensor.

4. The remote monitoring device of claim 1, wherein the at least one processor further causes the remote monitoring device at least to: adjust the estimated operating times based on a signal strength of the radio interface component.

5. The remote monitoring device of claim 1, wherein the at least one processor further causes the remote monitoring device at least to: adjust the estimated operating times based on actual power consumption measurements measured for one or more of the operating modes.

6. The remote monitoring device of claim 1, wherein the at least one processor further causes the remote monitoring device at least to: utilize a machine learning system (**1202**) to select between the operating modes during the future time period using the estimated operating times as an input parameter (**1210**).

7. The remote monitoring device of claim 6, wherein: the machine learning system is trained to balance maximum sensing capabilities (**1230**) of the at least one sensor with maximum operating time (**1232**) in selecting between the operating modes.

8. The remote monitoring device of claim 1, wherein: the mode selection process is triggered within the remote monitoring device based on an alert from an external server or neighboring remote monitoring device.

9. The remote monitoring device of claim 1, wherein: the mode selection process is triggered within the remote monitoring device based on a state of charge of the battery.

10. The remote monitoring device of claim 1, wherein: the at least one sensor comprises at least one of: a carbon dioxide sensor (**402**); a carbon monoxide sensor (**404**); a volatile organic compound sensor (**406**); a particulate matter sensor (**408**); a gas sensor (**410**); and a temperature sensor (**412**).

11. A method (**500**) of environmental monitoring in a remote monitoring device comprising power-consuming components and a power source configured to provide power to the power-consuming components, wherein the power-consuming components comprise at least one sensor and a radio interface component configured for wireless connectivity, and the power source comprises a battery and at least one solar panel configured to charge the battery, the method comprising: storing (**502**) mode information on a plurality of operating modes defining differing levels of sensing capabilities by the at least one sensor, wherein the operating modes have different power consumption profiles; and accumulating (**504**) energy information regarding solar energy collected by the at least one solar panel over a prior time period; the method characterized by: triggering a mode selection process within the remote monitoring device by: obtaining (**506**) environmental information regarding a location of the remote monitoring device over a future time period; calculating (**508**) estimated battery capacity data of the battery for the future time period based on the energy information and the environmental information; calculating (**510**) estimated operating times of the remote monitoring device when operating in the operating modes during the future time period based on the estimated battery capacity data and the power consumption profiles; and selecting (**512**) between the operating modes during the future time period using the estimated operating times, wherein the triggering comprises triggering the mode selection process within the remote monitoring device based on sensor measurements from the at least one sensor.

12. The method of claim 11, wherein the accumulating comprises: building (**514**) an hourly histogram regarding the energy information indicating a moving average of charging current measured at the at least one solar panel for each hour over a number of prior days.

13. The method of claim 11, wherein: the triggering comprises triggering the mode selection process within the remote monitoring device based on an elevated concentration of gas or particulates in the sensor measurements from the at least one sensor.

14. The method of claim 11, further comprising: adjusting (**518**) the estimated operating times based on a signal strength of the radio interface component.

15. The method of claim 11, further comprising: adjusting (**518**) the estimated operating times based on actual power consumption measurements measured for one or more of the operating modes.

16. The method of claim 11, further comprising: utilizing (**520**) a machine learning system to select between the operating modes during the future time period using the estimated operating times as an input parameter.

17. The method of claim 16, wherein: the machine learning system is trained to balance maximum sensing capabilities of the at least one sensor with maximum operating time in selecting between

the operating modes.

18. The method of claim 11, wherein: the triggering comprises triggering the mode selection process within the remote monitoring device based on an alert from an external server or neighboring remote monitoring device.

19. The method of claim 11, wherein: the triggering comprises triggering the mode selection process within the remote monitoring device based on a state of charge of the battery.

20. The method of claim 11, wherein: the at least one sensor comprises at least one of: a carbon dioxide sensor; a carbon monoxide sensor; a volatile organic compound sensor; a particulate matter sensor; a gas sensor; and a temperature sensor.