Energy efficient communication based on self-organisation of IoT devices for material flow tracking

Gašper Škulj ^a, Alojzij Sluga ^a, Drago Bračun ^a, Peter Butala (1) ^a, Rok Vrabič (2) ^{a,*}

^a Department of Control and Manufacturing Systems, University of Ljubljana, Slovenia

Material flow management is an increasingly difficult activity in today's ever-more-complex manufacturing systems. New approaches are offered by the industrial internet of things (IIoT), which is envisioned as a network of active devices that are capable of wireless communication. However, the dependence of IIoT devices on battery energy presents a maintenance challenge. The paper proposes a self-organisation-based approach to improve the overall energy efficiency of workpiece localisation using IIoT devices. A simulation study is performed to show the effects of transmitter effectiveness, material flow dynamics, and system scale on the energy efficiency.

Manufacturing system; Energy efficiency; Industrial internet of things

1. Introduction

Manufacturing systems are becoming more complex to meet the needs of the market, which include a growing diversity of products, a shortening of the time-to-market, and an assurance of high quality. As a consequence, the structure of manufacturing systems is becoming less rigid, aiming for greater flexibility and reconfigurability. New manufacturing structures require new supporting information and communication solutions to help with their management. Solutions based on cyber-physical systems, which intertwine the physical and the digital worlds, and the Internet of Things (IIoT), which enables the ubiquitous connectivity of devices, are increasingly being used [1].

A promising domain for industrial IIoT applications is the control of material flow, which itself is becoming more complex as a consequence of the greater flexibility and reconfigurability of manufacturing systems. Instead of the straightforward paths of workpieces through the system along conveyor belts, parts, with their movement between workplaces, create complex networks [2]. This is especially relevant in engineer-to-order environment, because it involves the manufacture, control, and assembly of parts in small series and on large time scales. For example, the duration of projects in engineer-to-order industries, such as aerospace and hydropower equipment, ranges from several weeks to several years. Because of the complexity of the material flow, the long time during which the workpieces need to be available in the workshop, and due to human error, information about the workpiece's location can get lost and, therefore, workpieces become misplaced.

These misplaced workpieces either need to be found or replaced in order to continue with the production process. In engineer-to-order environments, the workpieces are often of high value; therefore, replacing them is not an option. But misplacement also results in costs that arise from the delays in the production process and the time and effort spent for localisation.

A solution is offered by active IIoT devices that travel together with workpieces and are capable of actively communicating additional information about their state. Due to the fall in the prices of embedded electronics and wireless technology, the value of a potential loss of information (i.e., the misplacement of a

workpiece) is greater than the price of the introduction of a multitude of such devices. In the future, such systems will only become more cost-effective.

The problem caused by the implementation of the IIoT on a large scale is that the IIoT system itself must then be maintained. For active, battery-powered devices, a high energy efficiency is of great importance because it reduces the maintenance costs (e.g., the cost of replacing or recharging the batteries).

Using IIoT devices for material flow tracking means having to cope with another problem, i.e., that the amount and the locations of the tracking devices are constantly changing. To create a truly scalable system, new, distributed mechanisms need to be introduced for localisation. Such a system should be able to operate without a central authority, and the IIoT devices should be able to self-organise the communication, following a set of simple predefined rules. The paper proposes such a self-organisation-based approach for energy-efficient communication that is applicable to material flow tracking. It addresses the scenario of searching for workpieces, equipped with battery-powered IIoT tracking devices, on the scale of a workshop. Based on a simulation analysis, recommendations for designing IIoT-based material tracking systems are presented.

2. Wireless sensor networks

Interest in wireless sensor networks (WSN) in the industrial environment comes from the desire for real-time communications between the planning and the execution in production systems [3]. Advances in information technologies have allowed production systems to begin the transformation towards cyber-physical systems, relying on cooperative control, multi-agent systems (MAS), complex adaptive systems (CAS), emergent systems, sensor networks, and data mining [1]. The early stages of this transformation exposed a need for new methodologies, architectures, and frameworks to be used in the implementation of already existing information technologies [4].

Wireless communication is the key technology as it supports IIoT in the form of WSNs. Intensive research has produced a set of working wireless technologies and an extensive knowledge base regarding their application. WSN requirements have been identified as scalability, coverage, latency, quality of service, security, mobility, and robustness. Applications in different

domains require different levels of each requirement. To improve the energy efficiency of WSNs, several energy saving mechanisms were developed, such as radio optimisation, data reduction, sleep/wake-up schemes, energy efficient routing, and battery repletion [5]. To reduce the energy consumption, network topologies and communication protocols are also being studied and improved [e.g. 6].

Radio technologies that can be used to setup a WSN offer a wide range of property combinations [7–9]. The radio ranges vary from a few meters with ZigBee to a few kilometres with LoRa. Data transmission rates can be as high as a few hundred Mbit/s with Wi-Fi and as low as a few hundred bit/s with LoRa. When it comes to WSN radio technologies, ZigBee, Bluetooth/BLE, ANT, Wi-Fi, LoRa, and LTE are, along with others, often employed in practical applications. All wireless communication technologies have in common that they try to be as energy efficient as possible, while providing the desired communication range and data transmission rate.

The energy efficiency problem in WSN and IoT can be approached from different perspectives and the design decisions are primarily influenced by the application. This paper focuses on the organisational aspects of networked communication devices in an industrial environment, which require robust implementation. Self-organisation was chosen as the basis for the material flow tracking concept because it ensures the adaptability, robustness, and scalability of the network in a workshop environment with a complex material flow. Inspiration is drawn from the concept of a biological manufacturing system [10] that puts a great emphasis on the dynamic reconfiguration of a manufacturing system driven by biologically inspired ideas such as self-growth, self-organisation, adaptation, and evolution.

Self-organising communication networks achieve their global behaviour through local interactions. The conventional centralised approach to network design strives for perfect network coordination based on global optimisation. The design process for self-organising networks is, on the other hand, faced with complexities arising from the emergent global behaviour [11]. The concept of self-organisation was, for example, used to create protocols for self-organising WSNs with high energy constraints supporting only the slow mobility of the nodes [12] and a localisation sensor network system that can reproduce the spatial geometry behind the network topology [13].

3. Self-organisation-based workpiece localisation

Material flow tracking can be accomplished with an assumption that all the workpieces move through the workshop according to the production plan and/or through active workpiece localisation. The proposed solution for the active localisation of the workpieces introduces a self-organising energy-efficient system in which each device is responsible for ensuring that its corresponding workpiece can be located at all times. The behaviour of the device is based on rules that are designed to enable organisation as a consequence of the interaction between devices. The rules do not enforce a predetermined organisational structure, but rather promote the emergence of organisational structures that are appropriate for a particular situation.

Tracking devices that are used in this concept have the composition of a common wireless device and consist of a rugged housing, a battery, a microcontroller and a radio transceiver. The transceiver's transmission power determines the communication radius in which the messages can be received. The devices are attached to workpieces and have unique identification codes – IDs. When the device is turned on, it must incorporate itself into the system of other devices without an external authority.

All the devices behave according to the same rules. A device can be in one of two states: either active or in hibernation. When a

device is active, it is constantly listening for radio transmissions and periodically transmitting its ID. When a device is hibernating, it is essentially in deep sleep, where everything except for its wake-up timer is turned off. The active state requires much more energy than hibernation, but when a device is hibernating, it is not listening to radio transmissions and cannot respond to a request for its location. Some devices need to remain active and listen for radio transmissions on behalf of the hibernating devices in their vicinity. Which devices are at some point in time active and which are in hibernation is a result of the self-organising interactions. The interactions are the result of device behaviour, shown in Algorithm 1. Active devices keep a representee list, i.e. a list of hibernating devices that they represent. This list is updated by representation and cancellation requests received from other devices. If the device's representee list becomes empty, the device seeks to be represented by the closest active device and, if successful, goes into hibernation. Hibernating devices periodically send representation renewal requests and themselves become active only if there are no other active devices in their communication range.

Algorithm 1. Device behaviour pseudocode.

```

SET device state to active
REPEAT:
  IF device state is active:
    SEND device ID periodically (parallel execution)
    LISTEN and GET list of requests
    FOR ALL requests in list of requests:
      IF request is representation request:
        ADD device (requesting representation) to representee list
      IF request is localisation requests AND request is for device in representee list:
        SEND successful localisation response
    FOR ALL devices in representee list:
      IF time from last communication with device ≥ time limit:
        REMOVE device from representee list
    IF representee list is empty:
      LISTEN and GET list of active devices
      IF list of active devices is NOT empty:
        SELECT closest active device based on radio signal
        SEND representation request to closest active device
        SET device state to hibernation
    IF device state is hibernation:
      perform DEEP SLEEP for hibernation period
      LISTEN and GET list of active devices
      IF list of active devices is NOT empty:
        SELECT closest active device based on radio signal
        IF closest active device is the same as old representative device:
          SEND representation renewal request to closest active device
        ELSE:
          SEND representation request to closest active device
          IF old representative device is in list of active devices:
            SEND cancellation request to old representative device
        ELSE:
          SET device state to active

```

Legend: ACTION, *variable*, **value**, message

Localisation requests are sent by a human looking for a workpiece. The request includes the ID of the device that is associated with the workpiece. The transmission power of the request is as large as possible in order to inform as many active devices as possible. The device's transmission power is changed based on the location request's signal strength and its transmission power. The energy efficiency is, at this point, less important than the location information. If an active device receives a location request with the ID of a device that it represents, it starts continuously sending responses directly to the search initiator. The search initiator can then find the representation device by observing the signal strength and at the end of the search also recharges its battery.

4. Simulation study

The described concept for the localisation of workpieces in a workshop allows the tracking devices to organise themselves. Based on the expected concept performance, two hypotheses are provided:

Hypothesis 1: the resulting organisational structure has a higher energy efficiency than a system of unorganised devices that only listen for location requests.

Hypothesis 2: for a given size of workshop and number of tracked workpieces an optimal radio communication range can be determined in relation to the energy efficiency.

The concept was experimentally tested with a computer simulation where several key parameters were examined. The first parameter is the transmission effectiveness, which describes the communication hardware properties. The second parameter is a material flow dynamics (MFD) coefficient, K_{MFD} , which corresponds to a share of the workpieces in the workshop that move at the same time. The third parameter is the number of tracked workpieces N in the workshop. The system performance is observed through the average power consumption P_{SYS} of the system and the average location error ERR_{LOC} . The location error is the distance between the searched workpiece and its representative device.

4.1. Communication model

The communication properties related to energy consumption in the simulation, shown in Fig. 1, are the communication period T_C , the message transmission time T_{MSG} , the power required for listening P_{RX} , the power required for transmitting P_{TX} and the hibernation period T_H .

The communication period T_C defines the time available for all the devices to establish their future state and for the active devices to broadcast their ID. In the simulation the communication period T_C is constant and is used as the base for the time normalisation. The broadcast period T_B defines the time between periodical transmissions of a device's ID. The hibernation period T_H defines the time interval when the hibernating devices are shut down and is, in the simulation, equal to 50 communication periods T_C . A longer hibernation period T_H results in more energy savings, but a less responsive system, and a shorter hibernation period T_H results in less energy savings but a more responsive system. The system's responsiveness has a direct effect on the average location error ERR_{LOC} .

Fig. 1. Model of the energy consumption for communication in the simulation.

The energy required for listening E_{RX} is a product of the communication period T_C and the power required for listening P_{RX} , which is constant. The energy required for listening E_{RX} is the basis for the energy normalisation. The energy required for transmitting E_{TX} is a product of the message transmission time T_{MSG} and the power required for transmitting P_{TX} . The message transmission time is constant, because all the messages have, intentionally, the same length. The power for transmitting P_{TX} is set based on the desired communication radius R of the devices.

To simplify the relationship between the energy required for listening E_{RX} and the energy required for transmitting E_{TX} the communication profile abstraction (CPA) coefficient K_{CPA} was introduced. It hides the complexity of the RF transmission and is used to normalise the distances. The distance of 1 is equal to the communication radius R achieved between two transceiver radios with a CPA coefficient K_{CPA} of 1 and the energy required for listening E_{RX} during the communication period T_C , which is also normalised to 1. Based on Eq. 1 the normalised energy required for transmitting a single message E_{TX} within the radius R can be calculated.

$$E_{TX} = K_{CPA} \cdot R^2 \quad (1)$$

If the communication period T_C and the message transmission time T_{MSG} are constant, a lower CPA coefficient K_{CPA} means that less power is needed to effectively transmit a message within the communication radius. More effective transmitters are described by a lower CPA coefficient K_{CPA} .

Fig. 2. Snapshot of a self-organised network of IoT material tracking devices ($N=1000$).

4.2. Case study

In the simulation the workshop is assumed to be an idealised square area where workpieces move to simulate a material flow, as shown in Fig. 2. The initiation of the movement is random and depends on the workshop material flow dynamic coefficient. Workpieces move in a straight path for different periods of time. The resulting movement is an abstract representation of the material flow in a large workshop with many uniformly distributed workstations (e.g., a 50m × 50m CNC engineering-to-order workshop).

Fig. 3. Average power consumption P_{SYS} in relation to the communication radius R for different radio transmission effectiveness or CPA coefficients K_{CPA} ($N=1000$, $K_{MFD}=1$). The power P_{SYS} is normalised to the power consumption P_{SYS} at the communication radius $R=0$. The radius R is normalised to the workshop size.

The influence of the transmitter's effectiveness on the system is shown in Fig. 3. A higher transmission effectiveness or lower CPA coefficient K_{CPA} means that less energy is needed to transmit the same message inside the same communication radius R . If the communication radius R is 0, all the devices must listen for incoming transmissions and the resulting average normalised power consumption P_{SYS} is equal to 1. The positional accuracy is found to be independent of the radio transmission effectiveness or the CPA coefficient K_{CPA} .

Fig. 4. Average location error ERR_{LOC} in relation to the communication radius R for different MFD coefficients K_{MFD} ($N=1000$, $K_{CPA}=0.001$). The average location error ERR_{LOC} and the radius R are both normalised to the workshop size.

The influence of the material flow dynamics on the system is shown in Fig. 4. The material flow dynamics (MFD) coefficient K_{MFD} is equal to the share of moving workpieces in the workshop. In this experiment the localisation accuracy depends on both the communication radius R and the material flow dynamics. When the MFD coefficient K_{MFD} is 0, the average location error ERR_{LOC} is approximately 2/3 of the communication radius R . If the material flow dynamics is increased, a local ERR_{LOC} minimum is observed at radii from 2.5% at $K_{MFD}=1$ to 6% at $K_{MFD}=10$. The power consumption is less dependent on the material flow dynamics and has its minimum at a larger radius R (approx. 7.5% of the workshop size).

Fig. 5. Average power consumption P_{SYS} in relation to the communication radius R for different numbers of devices N ($K_{MFD}=1$, $K_{CPA}=0.001$). The power P_{SYS} is normalised to the power consumption P_{SYS} at the communication radius $R=0$. The radius R is normalised to the workshop size.

The influence of the number of devices N on the system is shown in Fig. 5. When the communication radius R is 0, the number of devices N directly corresponds to the value of the power consumption P_{SYS} . If the communication radius R is increased, the power consumption P_{SYS} is reduced towards its

minimum. For a larger number of devices N , the power reduction rate is greater. After the power consumption P_{SYS} reaches a minimum it starts to increase again. In this case, for a larger number of devices N , the power increase rate is smaller. The number of devices N has, on the other hand, a relatively small influence on the average location error ERR_{LOC} . At radii larger than 5% of the workshop size the influence becomes negligible.

5. Conclusion

The paper proposes a self-organisation-based concept for energy efficient material flow tracking, in which each IoT device is responsible for ensuring that its corresponding workpiece can always be localised. The concept introduces an energy saving mechanism in which active devices represent the nearby hibernating devices.

The simulation study confirms both hypotheses, i.e., the resulting organisational structure has a higher energy efficiency than a system of unorganised devices that only listen for location requests, and that for a given workshop size and number of tracked workpieces an optimal radio communication range can be determined in relation to the energy efficiency. If the combination of energy efficiency and the accuracy of location is considered, IoT devices used in material flow tracking that implement the proposed concept should have a communication radius equal to approximately 5% of the workshop size. This suggests that today's technologies such as Bluetooth (Class II) and ZigBee, which provide ranges up to a few tens of metres, are appropriate for the realisation of the approach.

The results of this research may offer a sound basis for designing energy efficient IoT material tracking systems for the factories of the future.

Acknowledgement

This work was partially supported by the Ministry of Higher Education, Science and Technology of the Republic of Slovenia, grant no. C3330-16-529000, and by the Slovenian Research Agency, grant no. P2-0270.

References

- [1] Monostori L, Kádár B, Bauernhansl T, Kondoh S, Kumara S, Reinhart G, Sauer O, Schuh G, Siyh W, Ueda K (2016) Cyber-physical systems in manufacturing. *CIRP Annals - Manufacturing Technology* 65(2):621-41.
- [2] Vrabčič R, Škulj G, Butala P (2013) Anomaly detection in shop floor material flow: A network theory approach. *CIRP Annals - Manufacturing Technology* 62(1):487-490.
- [3] Schuh G, Gottschalk S, Höhne, T (2007) High resolution production management. *CIRP Annals - Manufacturing Technology* 56(1):439-442.
- [4] Li W, Kara S (2017) Methodology for monitoring manufacturing environment by using Wireless Sensor Networks (WSN) and the Internet of Things (IoT). *Procedia CIRP* 61:323-328.
- [5] Rault T, Bouabdallah A, Challal Y (2014) Energy efficiency in wireless sensor networks: A top-down survey. *Computer Networks* 67:104-122.
- [6] Narayanaswamy S, Kawadia V, Sreenivas RS, Kumar P (2002) Power control in ad-hoc networks: Theory, architecture, algorithm and implementation of the COMPOW protocol. In *European Wireless Conference* 2002:156-162.
- [7] Tosi J, Taffoni F, Santacatterina M, Sannino R, Formica D (2017) Performance evaluation of Bluetooth low energy: a systematic review. *Sensors* 17(12):2898.
- [8] Mekki K, Bajic E, Chaxel F, Meyer F (2018) A comparative study of LPWAN technologies for large-scale IoT deployment. *ICT Express*, In Press.
- [9] Orsino A, Araniti G, Militano L, Alonso-Zarate J, Molinaro A, Iera A (2016) Energy efficient IoT data collection in smart cities exploiting D2D communications. *Sensors* 16(6):836.
- [10] Ueda K, Vaario J, Ohkura K (1997) Modelling of biological manufacturing systems for dynamic reconfiguration. *CIRP Annals - Manufacturing Technology* 46(1):343-346.
- [11] Prehofer C, Bettstetter C (2005) Self-organization in communication networks: principles and design paradigms. *IEEE Communications magazine* 43(7):78-85.
- [12] Sohrabi K, Gao J, Ailawadhi V, Pottie GJ (2000) Protocols for self-organization of a wireless sensor network. *IEEE personal communications* 7(5):16-27.
- [13] Takizawa Y, Takashima Y, Adachi N (2013) Self-Organizing Localization for Wireless Sensor Networks Based on Neighbor Topology. In *Proc. IARIA UBICOMM* 2013:102-108.