Enabling Sustainable Smart Neighborhoods

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***Abstract*—In this paper we provide a technical solution to combine the two factors automation and user motivation that help to implement sustainable smart spaces. To support these factors, commonly central components provided by energy providers or by public social networks like Facebook are used. Approaches that are based on a centralized architecture are problematic for various reasons, including making consumers dependent on a single operator, and introducing privacy risks.**

This paper presents the Distributed Smart Space Orchestration System (DS2OS), a fully decentralized approach for solving the connectivity problem in and between smart spaces. DS2OS connects entities of a smart space with each other and with trusted remote smart spaces of friends. A focus of the presentation lays on security, and establishing friendship relationships. The security is based on X.509 certificates for authentication. Secure friendship relationships are established by locally issued certificates for remote friends. This way a web of trust of distributed entities can emerge between spatially distributed smart spaces.

The presented solutions foster the emergence of smart neighborhoods by offering more flexibility and being more privacy-friendly than centralized solutions. Their use is illustrated with four scenarios for (a) Reducing Peak Demands and Demand Adaptation in Energy Consumption, (b) Neighbor Accounting and Distributed Energy Generation, (c) Neighborhood Coordination, and (d) Sharing of Data and Knowledge.

I. Introduction

Buildings and their devices consume about 26% of the overall primary energy production according to data from the U.S. and Germany [1], [2]. This corresponds to 40% of the overall non-industrial energy consumption. With 16% of the overall primary energy, private households are most important as they consume about 60% more primary energy than public buildings and offices. 70% of this consumption is for climate, lighting, and IT equipment.

Smart grids attempt to reduce the energy consumption. A common approach for smart grids is to remotely control the energy consumption at the customers' premises in order to reduce peak loads via better load balancing (see Sec. VII-A). Usually smart grids are controlled via software that is run by the energy provider. The topology is a star with the customers on the outside and the energy provider in the center.

Decentralized energy production in a neighborhood is another approach for reducing peak loads and the need for external energy supply. Local production can reduce the external energy footprint of a neighborhood. Pure energy consumers become energy producing prosumers. This approach usually does not involve much coordination as energy is simply sent to the power grid when it gets produced.

Besides shifting consumption (smart grids), and decentralized energy production, saving energy is another possibility for increasing sustainability. The US Department of Energy estimates about 30% of the current energy consumption to be avoidable [1]. Other studies estimate an energy reduction potential of up to 40% [3], [4]. Studies [5], [6] suggest that only by changing the consumer's behavior 20% less energy could be saved, which is half of the 40% non-industrial energy consumption. There is energy saving potential.

Practical experiments show that reducing the energy consumption is difficult to achieve. The author of [5] says that only 3-4% reduction of the energy consumption was achieved in a field test. Users failed to continuously comply with the energy savings recommendations. Long-term motivation seemed hard to achieve.

Smart grids and decentralized energy production do not involve the energy consumers much. Technology for involving the user, e.g. ambient signaling technology for creating awareness and incentives to save energy, is missing. Continuous feedback and ambient information are important to make users change their behaviors [4], [5], [6], [7].

With the Distributed Smart Space Orchestration System (DS2OS) this paper presents technology to manage all devices inside houses and between buildings in a decentralized way. The system facilitates and structures the creation of smart space services allowing rapid prototyping of scenarios including sustainability.

Today, households do not coordinate their activities. Especially coordination and cooperation between neighboring houses, offering spatial proximity that can be used to coordinate energy consumption, and between technically similar houses that are not necessarily spatially close, offering experience that can be used as recommendation knowledge base, are attractive for saving energy.

Neighborhoods are kind of a social network that in contrast to a friend-based social network does not form among friendship lines, but uses neighborship relations in the places of living. Explicitly introducing social relationships to implement technical connectivity allows to introduce orchestration over the homes of a neighborhood just like it allows exchange among friends in a classic social network.

After discussing the benefits of connecting spaces for common orchestration in Sec. III, the DS2OS middleware framework is presented (Sec. IV). Trust and transparency are fundamental for creating relationships between formerly unconnected smart space sites. The distributed security mechanisms of DS2OS introduced in Sec. V and Sec. VI, allowing secure coupling of spaces. The presented technologies are illustrated at the example of four scenarios (Sec. VII).

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II. Related work

Homes are gradually becoming smart. Smartmeters are being deployed and energy consumption has become a topic of interest for the general public. Users want to have automation system for environmental as well as financial reasons [8]. Consequently, large energy providers like German RWE have started to offer smart home technologies in their portfolio (RWE Smart Home [9]) leading to tight customer restraints.

It is not sufficient to add technology, it is also important to keep the users motivated [5], [6]. While there are people pioneering technologies in their homes, widespread adaptation is more under discussion than already becoming a reality [10]. Microsoft proposes that homes need an operating system and an app store as solution to many of the smart home problems [11]. Other companies like Google and Apple also proposed solutions in order to enter this market.

Efforts to build smart homes to save energy are manifold. Jahn et al. [12] have developed a prototype of an energy-aware smart home. Like in our approach the solution proposes to use a distributed middleware. The scientific decentralized approach contrasts centralized or cloud-based solutions that commercial products tend to follow predominantly.

Other solutions focus more on Smart grid technology where energy consumers become energy prosumers who also contribute energy to the SmartGrid system. The idea of an Internet of Smartmeters [13] is circulating and the functionality discussed for the meters goes well beyond energy monitoring. Energy profiles can be used in recommender systems to obtain personalized recommendations, e.g. to switch tariffs and predict and move load of energy consumers [14].

Security, and neighborhood and friendship relationships seem not to be highly relevant topics for industry and (consequently) customers yet.

III. Neighborhoods and Economy of Scale

Individual homes or apartments are small compared to large buildings, factories, or cities. Any optimization within such a small environment is limited to the possibilities this small smart space allows for. The situation changes when individual homes start interacting to form a combined entity.

As homes have strong potential for delaying non-urgent energy consuming tasks, a combination of homes may even have advantages to a factory with a comparable energy footprint. Within private homes there are a variety of devices where there is a delay-tolerance for energy consumption that could be utilized (e.g. refrigerator, dish washer, washing machine). Peak load reduction by delaying certain tasks will require less severe action per home if in a large neighborhood each home takes its share to achieve this goal. Connecting homes is desired as the energy saving potential scales up with the amount of connected entities.

Sharing resources between smart spaces can help saving energy. Going beyond pure private homes to offices, and other work or spare time environments, one can imagine that many smart space resources could be shared resulting in more efficient use that saves energy. Less personal spaces like offices, or shops are examples where resources like space, or equipment could be shared.

In case of office neighborhoods shareable resources could be meeting rooms and presentation areas. Typically, such spaces have low average utilization resulting in high energy saving potential via shared use. In the private sector specialized sensors (e.g. wind sensor), or even shared entities like repositories for energy (e.g. fuel oil) could be shared. Major obstacles for such resource sharing are missing technical solutions for access to the resource, and accounting.

This paper presents solutions that *enable sharing from a technical viewpoint*. But there are other obstacles including social challengess. A major challenge is responsibility. Today, resource sharing seems strange to be considered for private homes. Sharing apartments and living in them and customizing them on demand seem science fiction rather than reality. However, considering overpopulation and greenhouse effect consequences, chances are that this may become different in the future.

Shared resources tend to belong to "no one" and no one will care. Here, smart spaces and orchestration may help as technology can automate the operation of the shared resource, taking care of it on behalf of its users, and doing inherent accounting that can help identifying responsible bodies. Remote maintenance of smart spaces could become a new business model in the future. Remote maintenance technicians could get contracted for maintaining local equipment from remote in the future.

Sustainability should consider to utilize economy-of-scale effects, e.g. neighborhoods instead of only homes. If a larger number of users can reliably and securely access shared resources instead of individual resources, the number of required resources can be reduced. The secure orchestration system presented in the remainder of this paper can help to mitigate arising problems and become an enabler for smart spaces that allow sharing resources. While such solutions need that users accept the resource sharing, they do not require special user intervention and behavior to save energy as it can happen in a fully autonomous way as soon as the user installs (see Sec. IV) services that offer such functionality.

IV. Coordination and Cooperation Within and Between Smart Spaces

Connectivity is a major challenge for smart spaces to emerge today. Connectivity between hardware devices inside a smart space (home), and between smart spaces is usually not given though many spaces are enriched with embedded systems. Building sensors and actuators serve purposes like heating, ventilation, air-conditioning (HVAC), lighting, security, or entertainment.

A fundamental problem of technology enriched spaces is that the available and installed devices form silos. Systems are not compatible with one another [11]. This heterogeneity makes it challenging to collect energy consumption data, or to orchestrate devices of a space to optimize their energy consumption (e.g. by opening a window and shutting the air conditioning down when it is colder outside than inside).

Many commercial buildings offer solutions to the connectivity problem with so-called Building Automation Systems (BAS). Systems like BACnet connect predominantly the HVAC

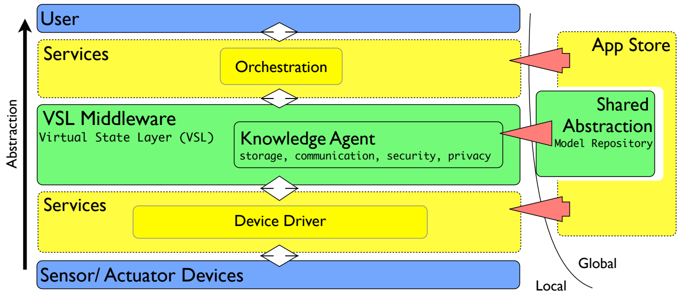

Fig. 1. The functional layers of DS2OS.

and lighting domains [15]. By doing so they enlarge the before mentioned silos but they are still not including other relevant domains like the IT infrastructure.
For homes professional BAS solutions are often too expensive and too difficult to maintain [8]. But also for private spaces like homes, components to sense and actuate spaces are available off-the-shelf [15], [16]. This makes automation scenarios realizable and attractive in home scenarios as well though the necessary software support is missing so far.

Middleware helps connecting and managing distributed entities. Existing middleware for smart spaces often serves a specific purpose like HVAC [17], or security and entertainment [18]. This brings the advantage that the middleware can support its specific use cases in an optimal way. This strength is at the same time a weakness as functionality for one use case is often not useful for, or even hindering other use cases. A general operating system for smart spaces is missing so far and thus sustainability cannot simply be added as a software service.

The Distributed Smart Space Orchestration System targets structuring and facilitating the orchestration of spaces via software services. It is a middleware framework that follows a different approach than many other middleware frameworks as it is built around a "μ-middleware", and extensible like a service oriented architecture. The term μ-middleware denotes that it only offers basic functionality in the core while being extensible similar to a μ-kernel operating system. This makes it more flexibly adaptable to different scenarios. As the μ-middleware core remains the common denominator, different scenarios become interoperable.

DS2OS offers core functionality that is common to orchestration scenarios in general only, including communication, security, storage, service portability, and service management. The major design goal of DS2OS is to structure and facilitate the orchestration of smart spaces, while offering a basis for realizing divers use cases and not introducing additional limitations.

The core of DS2OS is the Virtual State Layer (VSL) μ-middleware [19]. It offers communication, security, storage, and service portability. See Fig. 1. The VSL consists of so-called Knowledge Agents (KA) that span a distributed knowledge base overlay. All KAs are peers that run on distributed nodes, e.g. computers and embedded systems in a smart space. They are programmed in Java to run on various platforms.

The KAs configure themselves, the VSL heals automatically when KAs disappear, it is constantly optimizing itself as reaction to topology changes, it is protecting itself against attacks via encryption of the communication, and it is securing its data via encryption – the VSL is managing itself autonomously. This suits for the decentralized home scenario where administrators are not necessarily present.

The VSL uses generative communication over tuples [20] as main inter-process communication mechanism. The tuple space concept is adapted to smart spaces by introducing directed asynchronous communication. Directed communication fits better for smart spaces than anonymous communication as it matters which exact entities are controlled.

Asynchronism fits for many sustainability use cases as they do not have hard deadlines for execution. DS2OS introduces a latency below 200ms with its publish-subscribe communication. In the VSL, tuples in combination with publish-subscribe functionality allow full spatial and temporal decoupling of services. This facilitates the service creation significantly as developers do not have to care about these aspects. For services that need synchronous communication, the VSL offers remote procedure calls over pipes.

Services produce information and can store it into the address space of other services in the VSL to communicate with them. The VSL acts automatically as context storage for services, freeing programmers from implementing such functionality in each service.

The VSL information model is a hierarchically structured tuple space. The tuples represent properties of the physical reality. They can be grouped to trees, so-called *models*, that are named. The names of the models are the types of DS2OS. A type could be `/lighting/lamp` for instance, it could contain a sub node `/isOn` to reflect the state of a lamp and to allow switching it from a remote location.

All communication in DS2OS happens over the VSL and its abstraction, hierarchically structured tuples that form the models. Models are the abstract interfaces to services. They are globally shared over a repository (Fig. 1 right). Models enable *portability* for services as different instances, e.g. different lamps, can be controlled over the same interface, and services discover functionality based on the tapes instead of concrete locators. DS2OS fosters the necessary convergence of the models via distributed crowdsourced mechanisms [21].

Global sharing of the interfaces, and portability allow distributed development and sharing of services among spaces. Sharing is a purpose of the App Store that is also shown in Figure 1. Together with an autonomously working local service manager it allows technically inexperienced users to deploy services, and it maintains them without user intervention.

Services are used to connect devices to the VSL (bottom layer, driver) and to run orchestration logic (upper layer). The unified interfaces of the VSL facilitate mash-ups, and reuse of existing services resulting in simpler and faster development. The VSL can be adopted to any use case over installing suitable support services.

DS2OS acts as fundamental enabler for software-based sustainability. To run the scenarios described in Sec. VII, consumers only have to install the respective services to their space. Specialized technical knowledge becomes superfluous.

V. Distributed Identities

In traditional spaces location provides security. Non-networked devices inside a space (e.g. a house) can traditionally not be accessed from outside the physical limits of a space. With DS2OS devices become remotely controllable. To restore the protection virtual locality is introduced. The virtual locality is provided via certificates that define if an entity is a member of a virtual locality or not.

A virtual locality is called domain. Each domain runs a CA service that acts as local Certificate Authority (CA). The local CA is called Domain CA. It issues X.509 certificates to entities that belong to the domain. Typical DS2OS entities are KAs, services for connecting devices and running orchestration tasks, and users. A certificate contains the public key of the entity, its access rights, a validity period, and the public key of the domain. Entities that belong to a domain trust their own Domain CA. The public key of the Domain CA enables each entity to authenticate each other by validating their certificates.

All entities have to register with the site-local CA service. In this pairing process the owner of a domain has to acknowledge the identity of the entity and its access rights explicitly. The explicit pairing is important to make the integration of a (potentially harmful) software service explicit. In the pairing process, the user delegates rights to the paired entity for a certain time (validity period).

Each time a service connects to a KA it has to present its certificate. The KA validates the certificate using the public key of its domain. If the presented certificate is within the validity period the connecting service can access the VSL. To allow devices of friends or neighbors to access the local VSL, certificates are issued for them in the described way. Remote entities get paired with the local domain the same way local devices do as the virtual locality is spatially unbounded. Remote entities become trusted for the local site the long their certificate is valid.

VI. Context-based Circles of Trust

The mechanism described in Sec. V allows to add entities from other domains via the local Domain CA. Local and remote entities become part of a trust group. This way multiple webs of trust that span multiple smart spaces can be created. Introducing multiple webs of trust makes sense as people have multiple spheres of social interaction. Trust circles of the real world get mapped into the virtual space. This context preservation is important for determining context-related access rights for instance.

Each web of trust forms a social network with a specific goal in mind. One web should be about direct neighbors in the physical neighborhood. So, here the resulting graph is related to the geographic topology. Neighborhood orchestration services should only be able to operate over a certain limited distance in the neighborhood graph. Other webs could be certain groups of friends or family members. The assignments to different webs of trust do not have to be disjoint or consistent between domains. Family members might be reachable via the friend's web of trust, and the family web of trust for instance.

Web and distance in the web can be used for authorization. Different groups have different rights. While neighborhood relations may spread over multiple hops, going beyond the friends of friends distance in a family or friends network could be undesired. Friend relationships are especially interesting for social aspects of energy savings by competing with people regularly met in real life, exchanging ideas with trustees, and allowing smart space access to trusted people.

Different relationships could be set up in different ways. Physical neighbor relations could be set up by a local authority (e.g. facility management, digital plumber). Friendship relationships could be established by pairing of control devices (e.g. smartphone) when users meet physically, using technology like nearfield communication to certify each other. If physical meetings are impractical, existing social channels like social networks (e.g. Facebook) could be used.

Major benefits of having a decentralized trust architecture are user control and privacy. Users know their friends and can determine their physical neighbors. Cross-domain activities bare high security risks resulting in safety and privacy threats.

The presented mechanisms in combination with suitable UI mechanisms make security understandable even for technically inexperienced consumers. Storing the relationships in a decentralized form lowers the risk when one domain is compromised. Even though neighborhood relationships may be considered less critical for a user's privacy, being sparse with spreading information by not using centralized components that aggregate a significant amount of security relevant material helps protecting each consumer's privacy.

VII. Scenarios

With the presented technical solutions for connectivity, security, and creating communities sustainability scenarios can be implemented in a comfortable way. To illustrate the possibilities four scenarios are described using DS2OS. Energy saving figures for each scenario are described but it is future work to experiment with these ideas and measure actual reductions.

Resource sharing and knowledge sharing are the key mechanisms behind the scenarios. DS2OS organizes itself autonomously in a distributed way within one domain. Remote domains can be accessed via gateway agents that make parts of other domains visible in the local domain. Physical locality becomes irrelevant and is replaced by the webs of trust (Sec. VI). Services can transparently access information and request operations independent of the physical location of the entities they orchestrate.

A. Reducing Peak Demands and Demand Adaptation in Energy Consumption

Renewable energy sources do not produce energy according to demand, but according to their natural circumstances. One idea for smartgrids is that pricing and market mechanisms should make the demand follow the production. Energy orchestration can locally help to adapt the consumption to the demand. This is in itself not new, but is usually not put into the context of smart spaces. Given decentralized energy production in a smart neighborhood, the local energy production could trigger consumption that utilizes local daily peaks e.g. from solar panels.

Connecting all hardware that can be controlled over a DS2OS network results in a unified, vendor independent interface to the devices. Additionally the information model of DS2OS automatically leads to a classification of the devices into classes like heater, or fridge. Based on the classification of the devices and additional preferences users store in their personal DS2OS instances, local control services can help to consume energy when needed and reduce peak loads in general.

Reducing peak loads in one environment only is difficult as the peak loads may result from multiple environments, e.g. correlated activities in a whole neighborhood. The presented solutions overcome separation between neighbors allowing to use the given potential of scale (see Sec. III).

The presented security scheme allows to control the pairing with neighboring environments and it allows to exchange information in a secure way, including authentication and non-repudiation via logs. Energy providers can still play a supportive role in this scenario, but they are not required for the mechanisms to work. Allowing a decentralized decision process is more privacy-friendly than common solutions that advertise energy usage patterns to centralized cloud services.

The resulting energy saving potential depends heavily on the devices present in a neighborhood. The presented technology helps improving solutions by scaling the area of control up.

B. Neighbor Accounting and Distributed Energy Generation

While it is possible to share resources with neighbors today, there is no standard solution for accounting. Introducing standard mechanisms for accounting can become an important incentive to foster resource sharing in neighborhoods. Accounting is the basis for use-cases that include the sharing of resources in an unequal way.

With the presented technology no central authority like an energy provider is required to support accounting as the necessary data can easily be shared in the webs of trust and each entity is inherently authenticated. This enables local points of authority like owners of buildings and apartments to start accounting on the basis of contracts. Over-provisioning becomes less required.

The novel aspect here is that the energy generation can happen in the neighborhood as private accounting becomes possible via our technologies bringing incentives for sharing local investments. Additional to the partly established sharing of electricity (via decentralized production), neighbor accounting could lead to the emergence of new sharing domains like heat. With local sharing traditional energy providers would only provide the amount of energy that cannot be covered by the neighbors.

The overall savings depend on the actual use cases. As local energy consumption (use-case example above) can react to local energy production the overall disturbance that high-variance renewable energy sources put onto the energy grid is minimized.

C. Neighborhood Coordination

Neighboring households or offices influence each other in their decision-making and operation, which can be implemented as services operating in DS2OS. When a room is heated to 28°C and the room next door is cooled down to 17°C, the wall between the rooms and the air near-by bridge the heat from the warm room to the cold room. As a consequence, heating and climate controls of the two rooms operate against each other. The system will constantly produce heat on the one side and the self-produced heat will be cooled down on the other. This is an example of conflicting objectives in a smart neighborhood that wastes energy. There are certainly others.

The potential of smart neighborhood technologies is that the local control loops can be made aware of each other and cooperate. Without coordination neighboring controls can operate against each other due to conflicting objectives. With DS2OS, sharing information can become a regular operation.

Temperature sensors and their sensor fusion are important to measure the current state and compare the objectives in the different control loops. In the example case one might consider to a) ignore temperature sensors close to the conflicting area in asserting the right temperature. Furthermore, one may consider to b) reduce heating or cooling efforts close to the wall and increase them on more distant devices. So here, the high-level control of the heating devices is part of the orchestration system of one room.

Beyond this sharing of information and local reaction, mutual orchestration can become an option. One may imagine that the presence of a person could influence how important the system rates each of the conflicting objectives. So, without presence, each room may allow a deviation of 2°C from the temperature objectives. Orchestration would also allow to synchronize the operation of the devices, so they may either operate at the same time or only when the other is not operating, whatever is more energy-efficient.

Considering the widely accepted assumption [3], [4] that more than 20% to 40% of energy consumption in households and offices is wasted due to wrong operation and can be reduced by inducing the right behavior of technology and users, some of this is due to conflicting goals in their operation.

D. Sharing of Data and Knowledge

Rational monetary benefits do not motivate users enough to behave energy-efficiently [5], [6]. But people love sharing things with friends. As the friends do not necessary live nearby this is often not possible. The presented technical solutions removes the spatial separation between people concerning electronic information exchange of their equipment without the privacy-infringing usage of a public social networks like Facebook.

Establishing a social network among friends, allows to share knowledge, and to distribute average consumption values among a whole set of users. It allows to distribute experiences and best practices to enable inexperienced users to make the right decisions. As consumption values among friends or socially-related groups can be shared, gamification via competition among friends can provide additional motivation to overcome the usually careless behavior.

VIII. Conclusion

With DS2OS, this paper introduced technology for connecting devices inside a smart space, as well as for connecting smart spaces, and illustrated its use.

First the potential of connecting private spaces was discussed (Sec. III). It comes from higher degrees of freedom, avoiding of conflicts, and economy of scale effects.
Then the DS2OS middleware framework was introduced (Sec. IV). It providing secure transparent access to devices independent of their physical location. It provides service portability and offers an ecosystem for provisioning services to smart spaces. A decentralized solution like DS2OS has several benefits including information locality, protecting user privacy as information is not sent to central (cloud) servers that subsequently bare the risk of data breaches.
Next the security infrastructure was introduced (Sec. V). Its basis on local CAs and X.509 certificates was described. It was shown that the certificates allow to attach entities that are not physically close via adding them to a virtual locality across domains. Context-related webs of trust were introduced as semantics for controlling the spread of information, and to allow remote control. Different web of trust circles and ways to establish them were discussed (Sec. VI).
Finally four use cases were presented that illustrate the potential of the DS2OS technology (Sec. VII).
Technology for fully orchestrating spaces via software opens entirely new possibilities as realizing ideas becomes as simple as writing a program for a single computer system. Ideas for a more sustainable world become realizable at scale with all connected benefits while the tedious management and distribution details are handled by the DS2OS technology in the background.

We believe that the presented DS2OS technology and similar systems are the key for more sustainable environments as they help coordinating energy consuming hardware and giving advise to consumers. The transparent connectivity to data from all controlled entities allows to apply optimizations that are only reality in research labs today in real world smart spaces tomorrow. Especially via the described economy-of-scale, and the controlled interaction and sharing of resources between friends and neighbors we see strong energy saving potential.

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