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Deploying 5G-Technologies in Smart City and Smart Home Wireless Sensor Networks with Interferences

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Abstract Deploying 5G technologies in a combination of smart homes and smart city opens for a new ecosystem with big potentials. The potentials lie in the creation of an advanced ICT infrastructure with support for connected and entangled services possibilities including technologies for efficient communication in an Internet of Things (5G) contexts. In this paper we discuss some of the key challenges that exist in the smart city and smart home networks in the light of possible 5G-solutions. Focus is on deploying cognitive radio technologies (5G) which enables the smart city networks to support interconnected infrastructure elements, to handle big-data from the smart homes, and to be compatible with existing infrastructures. The considered cognitive radio technology is based on pre-coded OFDM which offers the needed flexibility to deal with the key challenges found in the smart home networks. Thus, it is able to overcome the WiFi interferences and the wall penetration losses for a limited power cost. By simulation it has been found that power saving in the range of 10–23 % can be achieved for a small bandwidth cost. Additionally, it has been found that the choice of the smart home gateway location can change its power consumption with 99 %. The developed simulator incorporates interferences, wall losses, and packet error rates, which is elaborated in this paper.

Keywords 5G-technology · Smart city · Smart home · Wireless sensor networks · Interferences · Cognitive radios

1 Introduction

Using a smart city ecosystem with the most recent ICT technologies and its services can create better, more cost efficient, and sustainable environments. A modern ICT based

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communication infrastructure can fuel a high quality of life based on sustainable economic development, including support for a wise management of scarce natural resources. Further, using ICT in a smart city context provides options for personalized health care, green ecosystems and intelligent community services. This paper discusses some of the potentials in applying "beyond 2020" communication technologies/5G in future smart cities and their infrastructure. General unfolding of technologies such as cooperative interference management, Internet of Things (IoT), and machine-to-machine communication and combining them in a common platform will be required to make the smart city the generator of solutions for wicked problems and the engine of transformations. Hence, a modern 5G based ICT infrastructure is needed which connects the smart homes and joins these into a smart city infrastructure. This infrastructure must combine IoTs, smart homes, and Cloud of Things (CoT) to a smart city homogeneous ecosystem, which can be divided into two groups: a smart city network (SCN) and a smart home network (SHN).

The SCN provides support for interconnecting the infrastructure elements with variable bit-rates, collecting smart homes big-data, and interfacing existing compatible infrastructures. The SHNs focus on challenges such as battery power in the context of interferences and wall penetration losses. They have to mitigate these challenges by using more transmit-power which drains their batteries [1]; however, by deploying cognitive radio (CR) that is assumed finally to be deployed in 5G they are able to deal with many of the core challenges found in a smart city ICT based ecosystem.

Using CRs in smart home nodes provide flexibility in form of deploying unused spectrum, avoiding emitting unnecessary interferences, and adapting pre-coded modulation in relation to the challenge type. Different technologies can be used to implement CRs; however, multicarrier waveforms like OFDM are often preferred due to their high flexibility in resource allocation and their high spectrum efficiency.

CR is thus a promising candidate for dealing with the smart city ICT based infrastructure challenges and this paper illustrates how a specific set of challenges can be met in a smart city ecosystem which offers supports for both the SCNs as well as the SHNs.

The SCNs are discussed in the light of the services and support offered by the CRs. These CRs are located in the smart homes, but they are interconnected by the Internet and the Cloud of Things (CoT) why they constitute a global virtual SCN.

The SHN challenges are discussed in a situation with WiFi interferences and wall penetration losses with a simulation model showing how much power is saved by selecting an optimal CR based gateway node between all the smart home nodes.

Below the paper is organized as follows: Sect. 2 provides an overview of related works. Section 3 provides an overview of the SHN and the SCN. Section 4 presents and discusses simulation of SHNs using CR technology in the smart home system. Section 5 discusses the simulated performance of SHN which uses CR technology. Simulation results and the achieved savings are explored. Section 6 concludes the paper by discussing the results in relation to the challenges.

2 Related Work

CR based frameworks for smart cities has been discussed by Vlacheas et al. [2] and they have provided a list with main issues which may prevent IoT from playing a crucial role. They propose a framework for handling these issues. Their framework does not provide a communication infrastructure and the CR-based infrastructure discussed in this paper is thus supplementing on this area.

A considerable amount of research has been done in the area of using OFDM based CR in wireless sensor networks (WSN) and challenges such as allocating frequencies and bit-streams have been researched extensively. However, using WSN in smart homes presents challenges such as handling interferences and penetrating walls which are more or less uncovered in the literature.

The interference level in smart homes is a key challenge because many devices and sources are contributing. One of the more serious is a WiFi access point which uses the IEEE 802.11b standard. This standard offers a frequency allocation of 14 channels in the 2.4 GHz band where each channel is 22 MHz wide and separated by 5 MHz, i.e. the channels are overlapping. Thus avoiding WiFi interferences in the ISM band at 2.4 Hz is a challenge. A promising approach is subdividing the spectrum into sub-channels and allocates them intelligently. Cavalcanti et al. [3] studied a CR-based WSN and found that CR-technologies have a great potential to improve spectrum access and enhance WSN performance. Similarly, Wang presents a method for optimal bit allocation on sub-channels [4] and Rana [5] propose an adaptive channel estimation technique for CR systems.

A similar challenge is the emitted interferences from the CR nodes embedded in a WSN. The main contribution is interferences from the spectral containment, i.e. leakage in the spectrum side-loops. Dikmese et al. [6] have presented an enhanced approach which deals with this challenge. They use a combined windowing and cancellation carrier technique, which reduces the problem considerably.

Another challenge in smart homes is the indoor penetration losses. Zhang et al. [7] have found that a 35 cm thick concrete wall has a penetration loss of 20 dB at 2.4 GHz and that the damping is proportional to the walls thickness. Similarly, they found that the penetration loss of a 12 cm thick uniform plaster board wall and a 12 cm thick slightly reinforced concrete wall have penetration losses in the interval of 5–10 dB.

As discussed, aligning the WSN node transmit powers provides a method to overcome the interferences. Kim et al. [8] suggest a RSSI based transmit power allocation scheme where the nodes exchange power information. However, this approach requires additional node complexity and resources.

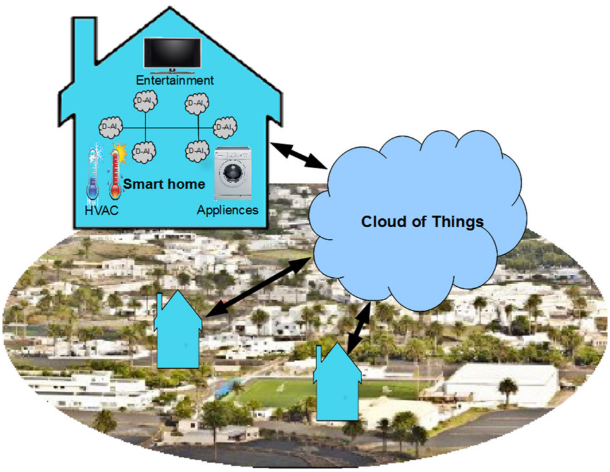


Fig. 1 A modern ICT based infrastructure for future smart cities

3 Smart City and Smart Home Networks

3.1 Smart City Networks

A modern ICT based smart city communication infrastructure must include SHN technologies which interconnects the IoT; CoT technologies which connects the smart homes; and cloud based service technologies which handles the smart city "big data" load. Such a communication infrastructure is illustrated in Fig. 1.

It comprises a collection of smart homes equipped with IoT's which offer services such as intelligent lighting, heating, security, and entertainment systems to its users. These IoT devices are interconnected by the SHN, which in turn is connected to the internet cloud services, i.e. one large virtual SCN or CoT network is created. This CoT network interconnects the smart homes and connects these to cloud services which consume the big-data produces by the smart home IoT's (sensors). Based on these big-data smart city services are offered.

Such a complex communication infrastructure must at least offer the following qualities to create an advanced SHN/SCN solution:

- Capacity to interconnect all infrastructure elements, i.e. scalable bit-rates is required.
- Capability to collect smart homes big-data, and offer complex services to the community, as well as to the individual smart home user.
- Compatibility with existing portable and fixed communication infrastructures in the smart city.
- Scalability, so it is easy to add new smart city members in the form of smart homes, upgrade and perform service to a distributed system, i.e. it must scale well.
- Easy access to all information and a simple interface to access the big-data on the cloud servers.

It is expected that the IoT devices embedded in the smart homes will produce a huge amount of information which needs to be stored and processed by the smart city CoT services [9]. CR is an obvious candidate to handle these communication challenges.

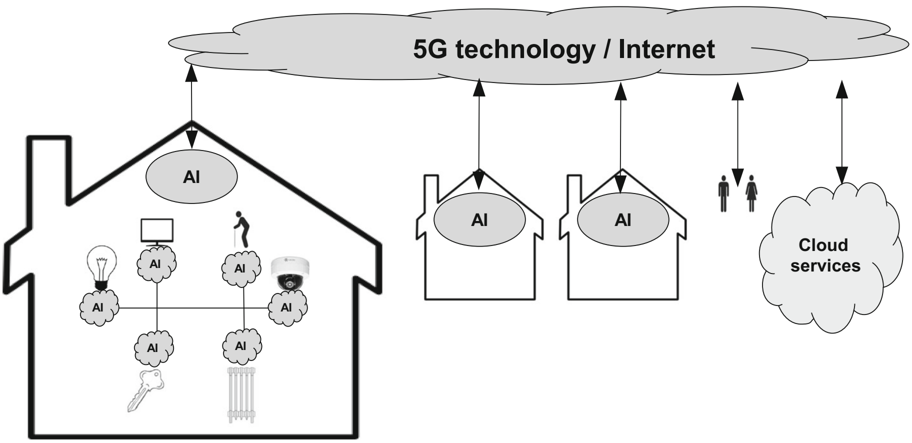


Fig. 2 Advanced integrated smart home and smart city infrastructure

Firstly, it offers local pervasive networks which means that the user can connect to several wireless technologies and move between them seamlessly. Secondly, different bit-rates as a function of spatial context can be offered by 5G topologies like multi-hop networks. Lastly, wearable devices, machine-to-machine communication, and Internet of Things (IoT) are enabled and supported.

CRs are able to interconnect all the smart city infrastructure elements by deploying multi-hop and pervasive networks. Likewise, they are able to scale their bandwidth by using opportunistic band allocation, which provides high bit-rates for transporting smart home "big-data". Thus, bit-rate demanding services can be offered to the community and the individual smart home user as illustrated in Fig. 2.

Additionally, the CR technology offers compatibility with the existing portable and fixed infrastructures used today, i.e. it is able to adapt to most of the used protocols. Hence, if the CRs are based on OFDM technology they can easily adapt commonly know OFDM based technologies such as WiFi, LTE, and WiMAX.

3.2 Smart Home Network Challenges

The key smart home network challenges are the wall penetration losses, the path losses, and the handling of WiFi access point interferences. These challenges are modelled and illustrated in Fig. 3.

The SHN illustrated in Fig. 3 contains a collection of connected sensor node groups where each group is terminated in a sensor end-device (triangles). These end-devices communicate with a router-node (circles) which in turn route communication through the SHN. Most smart homes contain a WiFi router which frequently interferes with the SHN nodes.

Analysing the path from the WiFi access point to each individual node some obstacles (crosses) are found. These can be either walls or furniture, but common for them is that they absorbs, diffracts and reflects part of the radio wave energy, i.e. these paths provide some damping. In addition, distance dependent indoor attenuation losses add damping as stated in [10]. Focusing at the paths between the SHN router-nodes (circles) they have similar problems, whereas the sensor end-nodes (triangles) often are mounted relatively close to the router-node why they are able to avoid most of the signal damping.

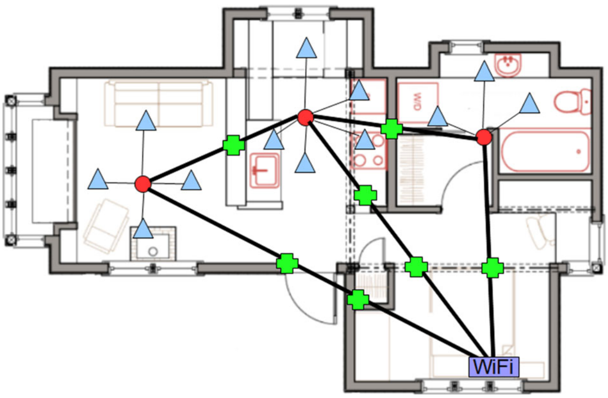


Fig. 3 A typical SHN with sensors (*triangles*), routing nodes (*circles*), and obstacles in form of walls (*crosses*) is presented. It includes a WiFi interference source together with its wall damping

Different methods have been used to deal with these challenges. In ZigBee networks the lower layer (IEEE 802.15.4) uses CDMA which spreads the spectrum to avoid single carrier interferences and multiple channels are available. However, the walls' and furnitures' damping still needs to be overcome by increasing the transmit power which drains the sensor node batteries. Another problem is that the interferences are only reduced by the limited CDMA processing gain. Other systems such as BT-LE use fast frequency hopping to cope with interferences, but in smart homes a huge amount of sensor nodes based on different wireless technologies will be deployed. This means that the frequency hopping schemes will not be able to obtain a reliable logic-channel and a sufficient bit-rate for many smart home services. For most of the established SHNs the bit-rate is too low to use error correcting coding as countermeasures for the damping provided by the furniture's and walls. However, a 5G OFDM based CR has the needed resources.

4 Simulation of Smart Home Networks with Cognitive Radios

As a 5G technology, cognitive radios are foreseen to be able to deal with some of the limitations found in SHNs. They will utilize spectrum in an opportunistic way in both the licensed as well as the unlicensed bands, they are able to increase communication reliability and energy efficiency, and they are able to provide opportunities to overcome SHN hardware limitations in software. Increased energy efficiency is achieved by reducing packet losses, change operation parameters like modulation, and adapt to channel conditions.

To illustrate the level of energy efficiency achieved by deploying CR technologies and selecting the gateway node optimally in a SHN environment with WiFi interferences and wall penetration losses a simulation model has been developed. A SHN simulation model, implemented and simulated on a mathematical tool running on a common PC deals with the discussed challenges by simulating the performance of the SHN nodes in terms of transmit power, interference level, additive white Gaussian noise, and packet error rates. Thus, the simulation model includes an indoor attenuation model, a mathematical model for predicting sensor packet losses, and a model for estimating the sensors energy consumption.

This simulation models has been used to analyze and exemplify the outlined challenges by using a dataset recorded in a smart home project researched by Kasteren et al. [11].

4.1 Wireless Propagation Model

As outlined the simulation model contains some sub-models which are discussed in the following. The first sub-model is the ITU indoor propagation model [12] which is described as:

$$L_{dB} = 20\log(f) + N\log(d) + P_f(n) - 28 \quad (1)$$

where L is the path loss in dB between two points separated by a distance d. The f parameter is the used frequency in MHz, the N parameter is a loss factor which depends on building type, and the $P_f(n)$ parameter is the floor loss penetration factor with n indicating the numbers of floors.

In this work the model has been modified by removing the floor loss penetration factor and adding a wall loss penetration factor $P_w(n)$ instead, where n is redefined to number of walls. This factor has been derived from the work performed by Bleda et al. [13] where they measured the damping factor of different materials such as woods, plastic and concrete. Their measurements are supported by Zhang et al. [14]. The modified and used equation is:

$$L_{dB} = 20\log(f) + N\log(d) + P_w(n) - 28 \tag{2}$$

The second sub-model predicts sensor packet losses by calculating the noise and signal values at the individual sensor position in the smart home. By using these values the energy per bit E_b divided by the noise spectral density N_0 can be estimated. Based on these results the Packet Error Rate (PER) can be calculated. Thus, the noise level from the disturbance source NLD_γ at sensor S_γ position can be expressed as:

$$NLD_\gamma = KTW + P_d/10^{L_{dB}/10} \tag{3}$$

where K is Boltzmann's constant, T is room temperature in Kelvin, W is the sensor communication bandwidth, P_d is power transmitted from the interfering source, and L_{dB} is given in Eq. (2). As implicitly stated by (3) it has been assumed that the transmission channel was characterized by additive white Gaussian noise (AWGN) channel and it only contained one dominant disturbance source. This disturbance source uses the same frequency as the sensor nodes. Additionally, it has been assumed that the disturbance source is located at a known distance away from the sensor node.

The signal power P_γ at sensor node S_γ can be found by dividing the transmitting source output power by the loss stated in (2) where the distance d is set to the distance between them. Combining the noise and signal levels yields:

$$\left.\frac{E_b}{N_0}\right|_\gamma = \frac{P_{\gamma+1}}{L_{\gamma,\gamma+1}} \cdot \frac{1}{NLD_\lambda} \cdot \frac{W}{R} \cdot \frac{1}{NF_\gamma} \tag{4}$$

where $P_{\gamma+1}$ is the transmitted output power from a sensor positioned at $S_{\gamma+1}$, $L_{\gamma,\gamma+1}$ is the indoor loss between the sensors, NLD_γ is the noise level from the interfering source given by (3), W is the used transmission bandwidth, R is the used bit-rate, and NF_γ is the noise factor for the receiver implemented in sensor S_γ.

By using the result from (4) the Bit Error Rate (BER) can be found as:

$$BER_\gamma \approx \frac{1}{\sqrt{4\pi \left.\frac{E_b}{N_0}\right|_\gamma}} e^{-\left(\left.\frac{E_b}{N_0}\right|_\gamma\right)}, \quad for \sqrt{\frac{2E_b}{N_0}} > 3 \tag{5}$$

From (5) the packet error can be calculated as:

$$PER_\gamma = 1 - (1 - BER_\gamma)^{8 \cdot NPB} \tag{6}$$

where it is assumed that the bit errors are independent of each other and NPB is the number of bytes in the received packet.

4.2 Cognitive Radio Pre-coding and Modulation Model

In communication systems there usually is trade-offs where some parameters are optimized at increased cost of others. Thus, one option for penetrating walls and combat interferences is increasing the transmit power which decreases the Bit Error Rate (BER), at the costs of

SHN battery lifetime. Alternatively, the BER can be decreased by deploying error correcting coding (pre-coding) without increasing the power consumption considerable; however, the bandwidth are sacrificed because pre-coding generates overhead information. In SHN battery powered sensors are common, why the discussed pre-coding approach is the best choice in this context.

In this paper a simplified model of an OFDM based CR is deployed. It offers reduced functionally, i.e. it is able to change spectrum allocation and add error correcting coding dynamically. It provides 16 orthogonal coded sub-channels (bins) with 64 Kbps each. Thus, the maximum achievable bit-rate is 1.024 Mbps. These values provide a good resolution where it is possible to combine bit-rates in a flexible way and thereby cover the spectrum of commonly used SHNs bit-rates such as ZigBee, BTLE, and 6LoWPAN [15]. Each bin (sub-channel) is modulated with BPSK according to the formulas (1)–(6), where no symbol scaling is performed for a cyclic prefix. The cyclic prefix has been left out of this simulation model because only a very short cyclic prefix is needed in "edge windows" based scaling to suppress the spectral leakage from the OFDM spectrum side-loops [6].

The simulation model uses two coding types to improve the BER without changing the transmit power; however some bandwidth expansion is needed for the 2/3-rate coder. First type is a Hamming (31,23) coder which has been chosen because it offers a very simple implementation [16]. The Hamming (31,23) coder produced 31 output bits for 23 input bits which adds approximately 25 % bandwidth overhead. For this cost it provided approx. 1.8 dB coding gain at a BER equal to 10^{-7} (Fig. 4). However, the expanded bandwidth used by the coder gives a loss of 1.5 dB, i.e. in total a gain of 0.5 dB can be achieved. This is equivalent to 12 % in transmit power and battery lifetime terms, if it is assumed that the transmitter is the main power consumer [17]. The second coder is a rate-2/3 convolutional coder which offers a good compromise between complexity and coding gain [16]. This coder provides a large gain, but for the cost of 3/2 bandwidth expansion. Thus, at a BER of 10^{-7} (equal to a packet error of approximately 10^{-4} for a packet size of 128 bytes) a gain

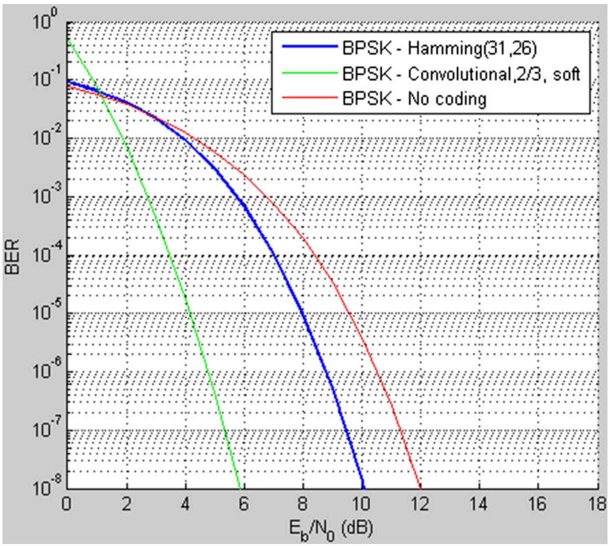


Fig. 4 The BER as a function of Eb/No for the used coders and BPSK modulation

of approximately 6 dB (Fig. 4) can be achieved for 1.8 dB bandwidth expansion loss or a total gain of 4.2 dB.

5 Simulated Performance of Smart Home Networks with Cognitive Radios

To quantify the performance of a CR-based SHN it has been compared to a commonly used Single Carrier Network (SCR). Their performance with respect to energy consumption, interference level, transmits power, and power consumption has been found by using the presented simulation model. For simplification purpose the non-routing sensor are named Reduced Functionality Devices (RFD). The RFD have been grouped into two groups (circles) and each group have been assigned a routing node, which is named a Full Functional Device (FFD) as illustrated in Fig. 5.

This model contains a WiFi access point (n_0) as the interfering source and two CR-based routing nodes (n_1 and n_2) symbolized by diamonds inclusive their respective sensor end-nodes (crosses). These end-nodes are resource constrained sensors with simple communication capabilities.

In this setting the Wifi access point needs to penetrate the walls in the bathroom and travel some distance before reaching the first node. Similarly, it needs to penetrate the bedroom walls, the kitchen wall and travel an additional distance to reach the kitchen router-node. The two router nodes need to penetrate the bedroom and kitchen walls and travels some distance for communicating.

Generalizing the SHN spatial topology and damping from Fig. 5 into a simplified attenuation model yields Fig. 6.

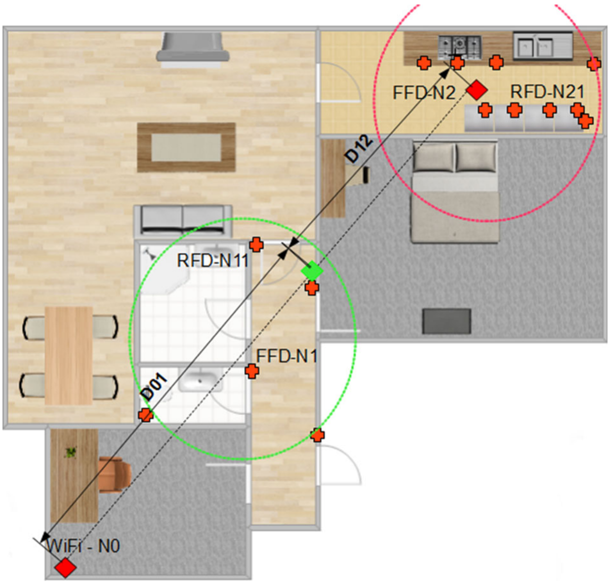


Fig. 5 The used SHN model including its routing and sensor placements (RFD-nodes). The *diamonds* are numbered: N0 is the WiFi transmitter, N1 is a CR-based FFD-node placed in the hall, N2 is a CR-based FFD-node placed in the kitchen, N11 and N21 are CR-based RFD-node, i.e. the sensor nodes. These sensor nodes are grouped into two mesh sub-networks bounded by the *circles*

Node n_0 is modelling the WiFi interfering source transmitting through the resistor l_{01} which combines the indoor attenuation loss and the wall penetrating losses. Likewise, nodes n_1 and n_2 models the two routing nodes connected through resistor l_{12}. Nodes n_{11} and n_{21} model the end-nodes (crosses in Fig. 5) with resistors l_{11} and l_{22} connecting them to their respective routing nodes. The arrows indicate the relevant flows of information and interferences. Thus, it is assumed that the end-nodes and their respective routing nodes are spatially placed close to each other and that they do not need to penetrate walls for communicating. This means that their interference and information levels can be regarded as being similar, i.e. only a unidirectional flow is needed to characterize their communication capabilities.

The common settings for the systems simulations are given in Table 1 and "Appendix". The numbers given in Table 1 have been used for the comparing the SCR and the CR simulations.

As illustrated in Fig. 7 the interference level at node n_1 considerably decreases the sensitivity of its radio which means that n_{11} and n_2 must use a considerable power level to communicate with it. Hence, node n_2 must use a transmit power level of 237 mW (non-coded) to penetrate the walls and to overcome the path loss when it transmits to n_1. However, when n_1 transmits to n_2 the WiFi signal is damped by the sum of L_{01} and L_{12}, whereas the signal from n_1 is damped by L_{12} only. This means that n_1 can use low transmit power (<1 mW). Regarding the end-nodes, it is noted that n_{21} are able to use low transmit power; however, n_{11} needs to increase its level to 2 mW to overcome the interference level at n_1.

By using coding the transmit power for n_2 can be reduced considerably compared to a SCR (Fig. 7). Comparing the non-coded CR power consumption of 266 mW with the SCR (237 mW) an increase of 11 % is noticed. However, the effective bit-rate has also increased from 400 Kbps (SCR) to 448 Kbps (CR) which is 11 %. Hence, this power increase comes from an increased bit-rate of the same size as the power consumption increases. Next, comparing the SCR and the Hamming coded CR (CR-HC) the power consumption drops from 237 to 213 mW or 10 % for the same bit-rate (400 Kbps). Furthermore, it is noted that the CR-HC uses a bandwidth of 512 kHz which compared to the SCR bandwidth of 550 kHz yields 7 % bandwidth savings in addition to the discussed power savings. Performing the same comparison between the SCR and the convolution coded CR (CR-CC) power drops from 237 to 174 mW, which is 26 %. But, the bandwidth used by the CR-CC is 640 kHz compared to 550 kHz for the SCR which is an increase of 16 %, i.e. power savings is traded for occupied bandwidth. Nonetheless, this increased bandwidth can be allocated at selected bins where there is some available spectrum.

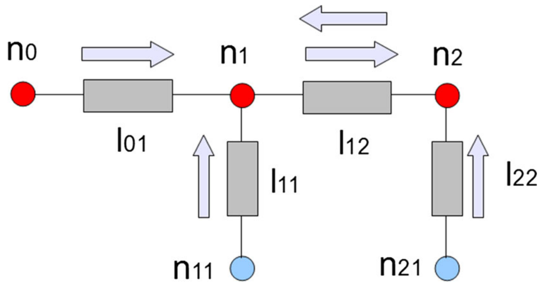


Fig. 6 A simplified attenuation model which covers the contributing parts of the used SHN model

Table 1 The simulation model settings used for the simulations of the SCR and the CR power performance

Parameter	SCR	CR
Payload bit-rate	400 Kbps	400 Kbps
Occupied spectrum, no coding (NC)	550 kHz	448 kHz (7 bins)
Hamming (31,26) coder (HC)	–	512 kHz (8 bins)
Rate-2/3 feed-forward conv. coder (CC)	–	640 kHz (10 bins)

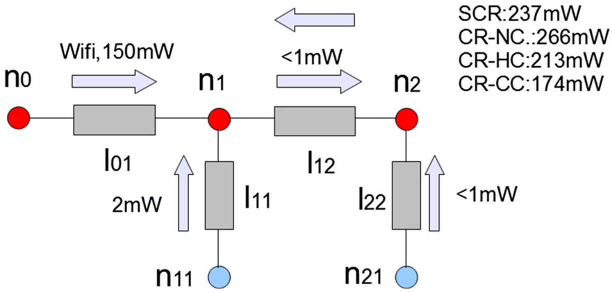


Fig. 7 Attenuation model containing the simulation results for the two placements P1 and P2 with the conditions of keeping the PER below 10^{-4}

By knowing the nodes transmit powers and the transmit time per event the energy consumption for each node can be calculated. For this calculation it is assumed that only the transmit power contributes [18]. This is a reasonable assumption because most small embedded wireless sensor devices uses low power single chip microcontrollers which do not use more than a few milliamps with a supply voltage of 2 V, i.e. normally less than 5 mW [19].

Assuming that 256 bytes are transmitted for each event, with a bit-rate of 400 Kbps, and the simulated transmit powers for node n_2 the energy consumptions has been found. These results are illustrated in Fig. 8.

Regarding on the best choice of gateway node n_2 is the best choice. This is because n_1 uses less than 1 mW to send to node n_2 (Fig. 7), whereas node n_2 must use 237 mW (un-

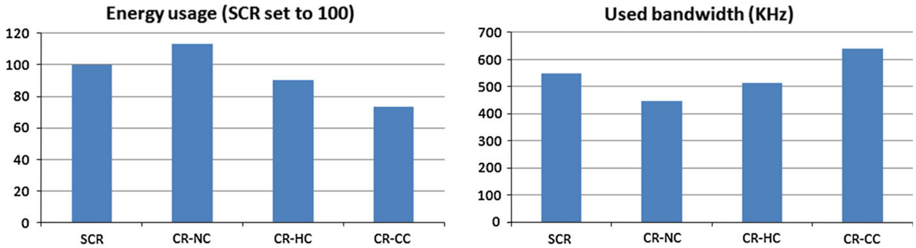


Fig. 8 *Left-handed* the normalized energy consumption for transmitting a smart home event. SCR has been normalized to 100 and the consumption of the CRs with different coding types are scaled to this normalized value. *Right handed* bandwidth (in KHz) occupied

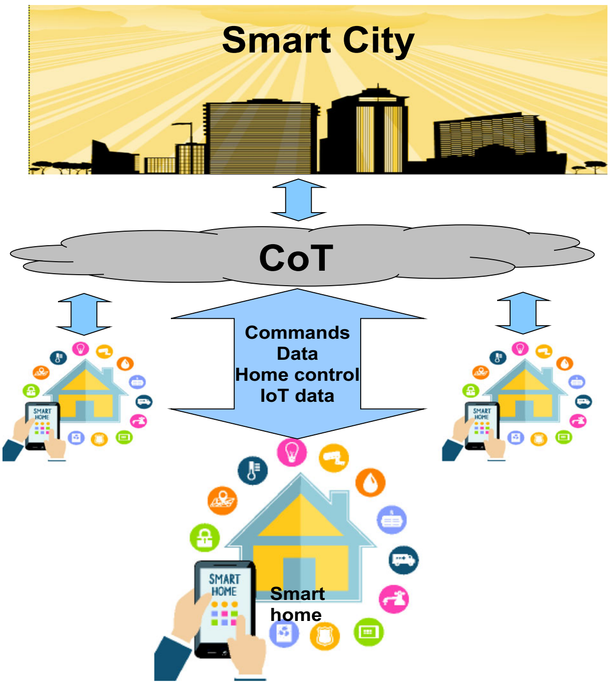
coded) to reach node n_1. Thus, letting the CR-based node n_2 function as both a routing node in the SHN and at the same time let it be the gateway to e.g. the WiFi router savings would be 236 mW or relative to 1 mW it is 99.6 %.

6 Integrated Smart Home and Smart City Visions

The CR enabled SHN with the above described spectrum flexibility and power saving illustrates that it is realistic to integrate a multitude of things in the Internet with most devices in the home being Internet-addressable. Introducing in this setting context-awareness and artificial intelligence, will pave the way for IoT's to become an important part of the future smart homes and smart cities.

In a future perspective this development will provide useful coupling between people, things and between things themselves. In the smart home context the connected devices contribute to make the home smart by sensing their context, reflect over their usage, and communicating this knowledge to the smart home management system. Thus, the connected devices contained in the smart homes capture contextual information that describes the ongoing activities. By using artificial intelligence to analyze the provided information the smart homes are able to learn the user's behaviour. The IoT's embedded in the smart homes thus produce contextual information, which is intelligently processed by the smart homes. Taking the next step by combining the smart homes into one large organic unit, the Smart City provides basis for developing new services and new infrastructures where the

Fig. 9 Smart homes and their embedded IoT's are combined by CoT technologies into a smart city infrastructure



smart homes are the knowledge suppliers handled in a new communication concept and providing the platform for a new ecosystem offering services according to our preferences as illustrated in Fig. 9.

7 Conclusions

Deploying a CR based infrastructure in smart cities and smart homes as part of the emerging 5G offer a promising new ecosystem with potentials as a welfare oriented change driver.

At the basic, technical level it has been illustrated that deploying CRs in smart homes offer ways to handle the smart homes key challenges which are interferences and wall penetration losses for a limited power budget. Simulations have been performed to answer the questions raised in the introduction about what power performance can be achieved with a CR solution under different conditions. These simulations compare a commonly used SHN with a 5G based on CRs with OFDM pre-coding. It has been found that the CR approach provides considerable power savings compared to the commonly used SHN approach. Thus, using the CR based approach with Hamming (31/23) coding saves 10 % power and 7 % bandwidth. Similarly, using a rate 2/3 convolutional coder provides 26 % power savings, but for the cost of 16 % bandwidth expansion. Thus, SHN battery energy consumption and thereby battery lifetime can be extended with as much as 26 % by adding simple coding, for a limited cost of bandwidth. Additionally, savings of 99.6 % has been found by using a selected CR-node to handle both the routing and gateway functionality.

However, these savings comes for a cost. Firstly, more complexity is added in from of software for handling the CR-part. Secondly, achieving large power savings means sacrificing bandwidth.

At the socio-technical level it has been illustrated that CRs can contribute to the handling of many of the SHN/SCN communication needs by offering the basis for 5G communication technologies such as pervasive networks, opportunistic spectrum allocation, and multi-hopping. These communication technologies provide solutions for the smart city challenges such as interconnecting infrastructure elements with scalable bit-rates, capability to collect smart homes big-data, compatibility with existing wireless systems, and scalability to add new citizen services based on online collected and processed user requirements.

Realization of the illustrated visions requires research and standardisation at the technical level before it is possible to interconnect and interface devices and systems. At the socio-economic level research and political agreement at the socio-economic level is required before it is possible to represent the user needs and requirements in way that can be used as input and feed-back in the SCN.

Finally, the technology is not available at a commercial level.

Appendix

The common settings for the systems simulations

- Frequency 2.4 GHz
- Receiver noise figure 10 dB.
- Distance power-loss coefficient (ITU model) 28
- Packet size (number of transmitted bytes) 128

- Packet error rate at all nodes 10^{-4}
- SCR RRC filter roll-off coefficient 0.25
- SCR FDM guard bands 10 %
- n0: WiFi/802.11b, 2.4 GHz, 150 mW output power
- l01: 6 m, 10 dB wall damping
- l11: 2 m, no walls
- l12: 4 m, 20 dB wall damping
- l22: 2 m, no walls

The settings for the CR modulation and multiplexing (OFDM) part:

- Number of sub-carries (bins) 16
- Spectrum per bin 64 kHz

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