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ENERGY-EFFICIENCY METHODS IN COMBINED WIRELESS SENSOR NETWORKS

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***Annotation**. The energy efficiency is a critical requirement in the wireless sensor networks (WSN) to ensure their long life, to reduce maintenance costs and to increase reliability. This can be achieved by a combination of different methods as placement of wired and wireless nodes, energy-efficient communication protocols and routing algorithms as well as event-based sampling. A successful application of these methods requires a mutual harmonized design at different levels of the systems. This paper depicts how these methods are realized in the planning tools CANDY Wireless Site Finder and CANDY Trace Router that provide optimal combined wired and wireless topologies under considering of costs, distances, transmitted power, frequencies, propagation environments (in-door/out-door) and obstacles given in CAD-compatible formats. The energy-efficient design is demonstrated at different system levels.*

Keywords: Combined Wireless Sensor Networks; Computer-Aided Design; Event-Based Control; Intelligent Sampling Model; Middleware.

***Аннотация.** Эффективность использования энергии является важным условием в беспроводных сенсорных сетей (WSN) для обеспечения их долгой жизни, чтобы уменьшить расходы на обслуживание и повысить надежность. Это может быть достигнуто путем комбинации различных методов, как размещение проводных и беспроводных узлов, энергосберегающие коммуникационные протоколы и алгоритмы маршрутизации, а также на основе событий выборки. Успешное применение этих методов требует взаимных согласованных дизайна на различных уровнях системы. Эта статья описывает, как эти методы реализованы в инструменты планирования CANDY беспроводной сайта Finder и конфеты Trace маршрутизатора, которые обеспечивают оптимальное комбинированных проводных и беспроводных топологий при рассмотрении расходов, расстояния, передаваемой мощности, частоты, распространения среды (in-door/out-door) и препятствия, приведены в CAD-совместимые форматы. Энергоэффективного дизайна демонстрируется на различных уровнях системы.*

Ключевые слова: комбинированный беспроводных сенсорных сетей; автоматизированного проектирования; на основе событий управления; Интеллектуальная модель выборки.

I. INTRODUCTION

The overview about up-to-date wireless networks is given in [1, 6, 11, 12]. The wireless sensor networks gained nowadays their maturity and play greater meaning year-by-year for industry manufacturing, intelligent houses, automated ambiences and monitored out-door areas (in health, agriculture, forestry, ecology and navigation) and so on. The advanced WSN are integrated together with communication networks LAN and WLAN as well as with proprietary networks like in home automation (e.g. EIB, LON) and industrial automation (e.g. CAN, Profibus), cp. Fig. 1. In the given picture an automated ambience is shown with a combined network.

A wireless sensor network consists of spatially distributed, autonomous sensor nodes (SN) to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants. The integration with communication networks LAN and WLAN indoor via gateways (GW) offers possibility of further measurement data processing with use of access means

Web interfaces and Web Services as well as middleware (MW). Control of measurements can be also supported via modern PDAs (WLAN, Bluetooth), e.g. an i-Phone with installed specialized apps.

One of the most important problems of WSN is the energy efficient wireless sensor networking [1 – 3]. The energy efficient sensor nodes will provide long-live functionality as well as reduce their modification costs and increase reliability. Simultaneously, the inter-operability and quality of service requirements should be fulfilled by the constructed WSN.

The advanced sensor nodes with energy harvesting functionality have to be rationally placed and try to find optimal routes to the gateway (GSN). Therefore, the software solutions (OS, applications, API – Application Programming Interface, MW – Middleware) have to be very compact too. The tasks and the processed data have to be effectively scheduled and clustered [4 – 6]. For minimization of energy consumption by SN – SN and SN – GW communication as well to increase the GW-performance, the concepts of caching, threading and redundancy/replication have to be considered.

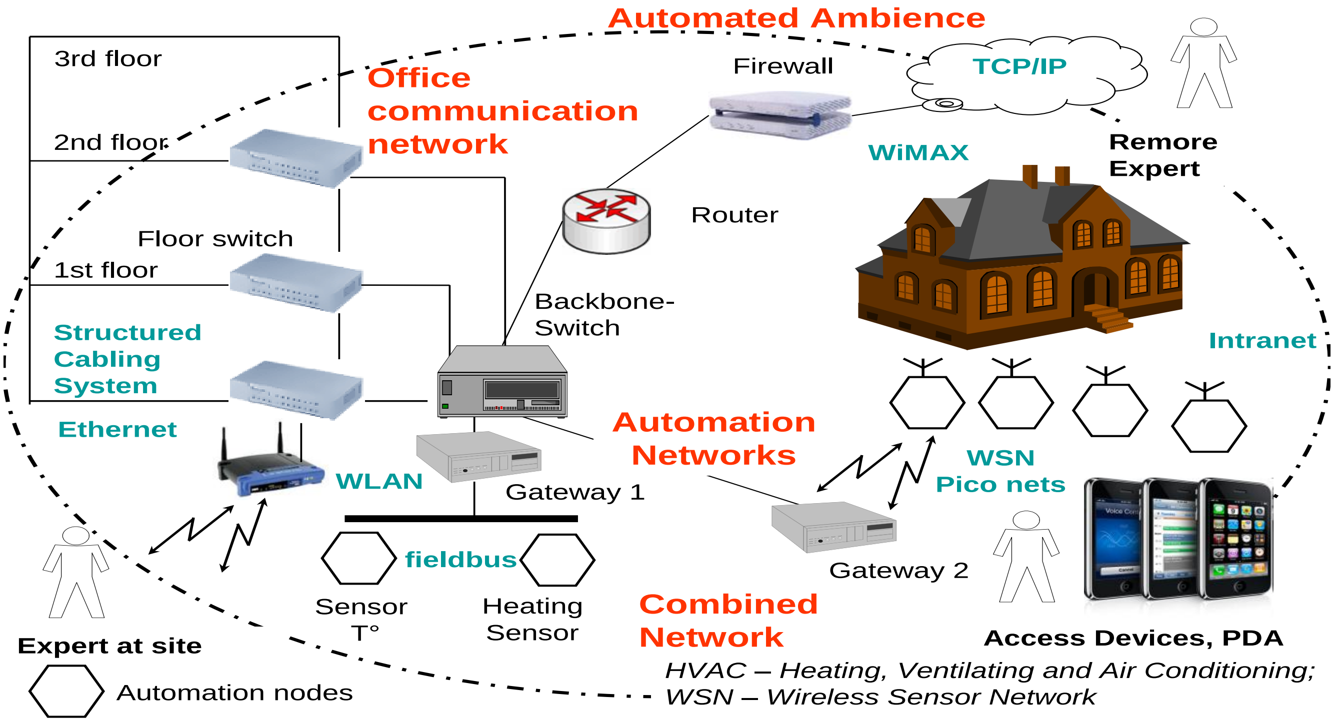

Figure 1 - Structure of a combined wired and wireless as well as intranet and home automation network.

This paper concerns the design of energy-efficient combined networks. Such networks include different technologies (i.e. wired and wireless connections with different communication protocols) and may be multipurpose (e.g. office or home intranet, industrial and home automation). The approach for gaining at different levels of the networks are recapitulated and a corresponding approach for their design is described.

II. CONSTRUCTION REQUIREMENTS AND METHODS FOR ENERGY EFFICIENT WSN

Nowadays, design of WSN is supported by a multitude of energy management methods and planning tools. The proposed cross-layer approach combines the existing models, methods and tools in an integrated framework [2, 3] and brings a large advantage due leveraging of multiple tradeoffs between the factors for energy consumption (Fig. 2). The important requisites of energy efficient WSNs are formulated below [1 – 3]:

1. Efficient power sources of wireless nodes including long-live batteries or energy harvesting methods as well as power management mechanisms.
2. Efficient protocols (OSI layers 2, 3) with reduced traffic and overhead.
3. Efficient operation systems and applications. For example, the event-based approaches in WSN allow the effective use of power management mechanisms.
4. Optimized topology (cabling traces, placement, hierarchy, clustering) as well as redundant planning and functionality reservation [7 – 10].
5. Harmonized design, also called cross-layer design.

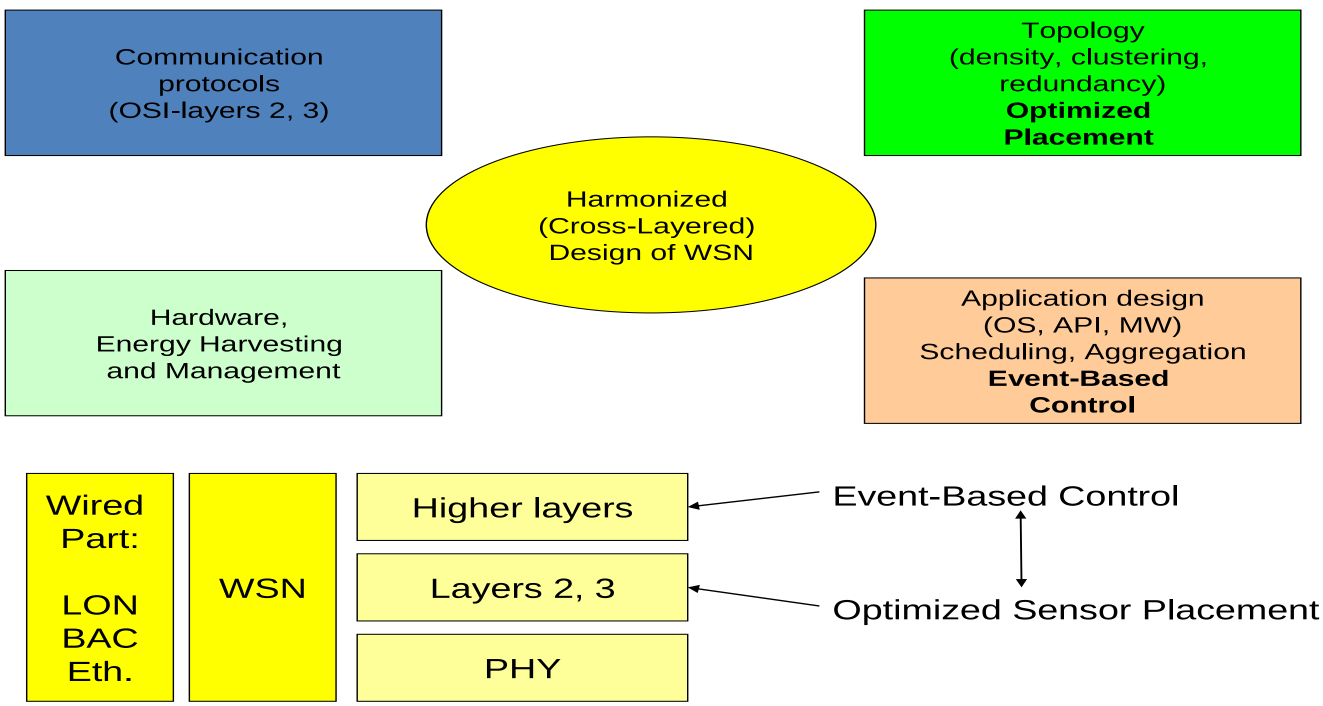

Figure 2 - Harmonized design of combined networks.

The positions 3, 4 and 5 of this enumeration are illustrated below more detailed. In particular, following energy efficiency aspects of WSN are focused on:

1) optimal placement of network elements (primary the wireless sensors) with the help of specialized tools for wireless networks design; as well as

2) configuration of event-based nodes in WSN.

The both points of gratitude allow elaboration of the concept for harmonized design for energy-efficient wireless sensor networks.

III. OPTIMAL PLACEMENT OF NETWORK ELEMENTS

This chapter discusses the CAD (Computer-Aided Design) tools of combined networks for offices and building automation systems based on diverse wired and wireless standards [6 – 9, 13, 14]. The design requirements on these networks are often contradictive and often have to consider performance, energy and cost efficiency for a network solution altogether. The accent is shifted to such design object like wireless sensor networks (WSN). The design tools are offered as well as the case studies for optimization of QoS, energy efficiency and overall-costs within combined networks are presented.

The optimal placement and tracing methods are realized in a CAD tool CANDY Framework. CANDY Framework consists of a set of Java tools for planning of wired and wireless nets (LAN, WLAN, WiMAX, wireless sensor piconets etc.) [7]. Exact planning with satisfying of QoS and energy efficiency is necessary in order to build cost-effective and efficient wired and wireless networks. The CANDY Framework [6 – 9] consists of a number of tools intending to support and simplify network planning. The following modules belong to the framework: 1 – Project Manager; 2 – Network Editor; 3 – Component Browser; 4 – SCS Trace Router; 5 – Wireless Site Finder; 6 – Workload Analyzer; 7 – Bill Reporter; FE – Front-end based on XML and NDML notations; T – Loose-coupled and 3rd party tools, like, for instance, NS-2 [7]; DB – Component repository (Fig. 3).

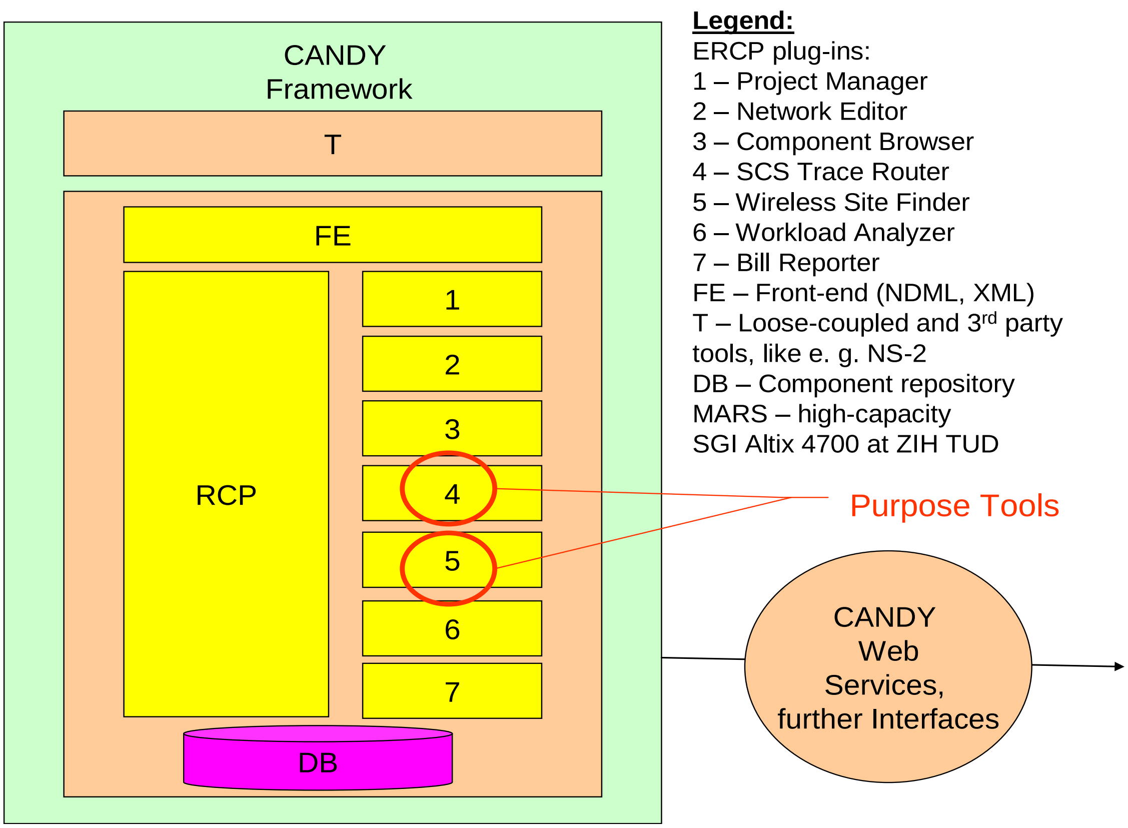

Figure 3 - Architecture of CANDY Framework

The NDML [6] is as a special interfaced XML-notation for description of combined network elements: switches, routers, GW, patch fields, cross panels, base stations, sensors, access points as well as automation nodes. To solve the tasks of optimal placement and tracing, the following tools are used [6]:

1. CANDY Wireless Site Finder (CSF) for optimal wireless topologies under considering of transmitted power, frequencies [6, 15, 16], propagation environments (in-door/out-door) and obstacles given in CAD-compatible formats (IFCXML-compatible AutoCAD format).

2. CANDY Trace Router (CRT) for optimal automated tracing of the structured cabling systems within the buildings with specification of server rooms (for switches, routers, GW, patch fields, cross panels) in CAD-compatible formats (e.g. IFC-XML) based on modified Dijkstra algorithm.

TABLE I. THE FUNCTIONAL FEATURES OF CANDY WIRELESS SITE FINDER

Supported wireless technologies	WLAN 802.11b	+
	WLAN 802.11g	+
	WLAN 802.11 a/h	+
	WiMAX 802.16	+
	Zig Bee 802.15.4	+
Geometry models	One floor (single layer)	2,5 D
Geometry import	Background image	JPG, GIF, PDF
	IFCXML	+
	NDML	+
	PythonCAD	+
Database of network devices	Devices, Base Stations, Access Points	2 WLAN, 2 WiMAX, 1 WSN
	NICs, GW	21 WLAN, 2 WiMAX, 1 WSN
	Extensibility	XML-interface
Material databases	Walls	6 types
	Extensibility	via XML, Eclipse RCP plug-ins in Java
Antenna models	Omni-directional	2,5 D

The tool CANDY Site Finder (CSF) realizes the following functions (cp. Table I):

- import of AutoCAD, PythonCAD, NDML, IFCXML, PDF floor plans, city maps, background images; export of XML, JPEG, BMP, PNG files;
- comfortable management in form of adding, changing, and removing of objects;
- automatic placement of AP/BS/SN;
- computation and visualization of the following propagation models: Free Space Loss, Multi Wall, COST 231 Walfish Ikegami, Dominant Path Prediction, and Line of Sight.
- visualization of attenuation, receiving power, DR and coverage [7 – 10].

The results of placement of WSN nodes planned with use of CSF tool are demonstrated in Fig. 4.

The tool CANDY Site Finder (CF) deploys the multiplicity of models and algorithms for WLAN/WiMAX-nets as well as WSN combined design. The overview is given in Table II. The models/algorithms are classified regarding to used technology (WLAN/ WiMAX/ WSN), deployed parameters and purpose area (category), usage modes (indoor/outdoor) and their computational complexity (expressed below via Landau-symbol).

A parallelized run-time environment based on Web Services and the solutions for computation-intensive models for CANDY Site Finder are under construction. Certain of them (e. g. for DPP model) have been implemented on the powerful SGI Altix 4700 at ZIH@TUD (1024 dual-core Intel Itanium processors and 6,5 TB main memory) and discussed in [9].

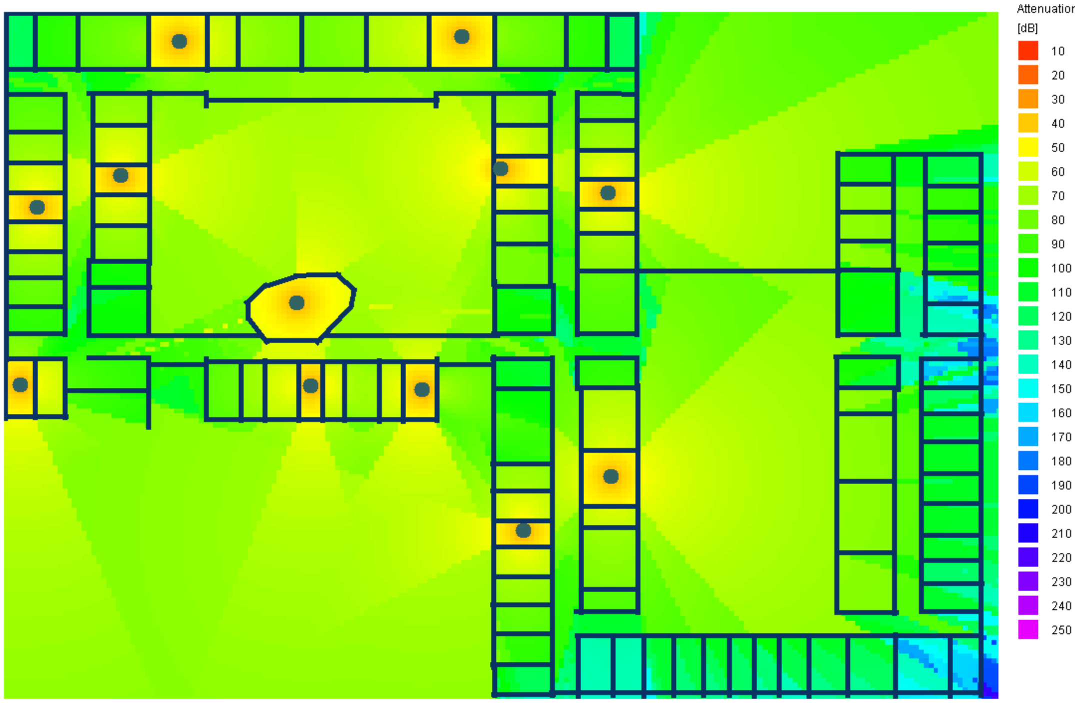

Figure 4 - WSN planning results with use of CANDY Site Finder

The in CANDY Trace Router (CRT) implemented Dijkstra tracing algorithm belongs to the class of sub-optimal „greedy algorithms" and calculates shortest paths from the start node to all other nodes for the defined cable channels and coupling elements positions. The complexity of the algorithm is $O(n^2)$.The structured cabling systems length for LAN and the wired part of the combined network as well as the overall combined network costs are minimized [6].

IV. EVENT-BASED ISSUES IN WSN ON THE EXAMPLE OF EVENT-BASED CONTROL

A. Event-based Issues in WSNs

The power management methods allow the adjustment of the computing power of the node and, correspondingly, its power consumption to the actual needs. This requires an appropriate event-based programming paradigm, which runs the applications only on occurring of proper external (e.g. wake-up signal or sensor value change) or internal (e.g. timers) events, reducing the number of redundant runs. This paradigm is supported by modern operation system for WSNs, e.g. TinyOS. However, the energy-efficient design requires not only event-based implementation, but also realistic evaluation of the event dynamics that is possible only if the application dynamics (e.g. development of the observed signals) and its configuration are evaluated. This aspect considered in this paper on the example of the event-based controls. To unify the possible configuration variants, an appropriate notation is described below.

B. Event-Based Control Configuration Notation

A brief notation is introduced for a quick reference of the corresponding configurations of event-based controls, which combines the notation of loop elements and the connection configuration of the nodes. The notation is described as:

$$I_x - S_{x-x} - C_{x-x-x-x} - A, \qquad (1)$$

where I, S, C and A denote the loop elements, namely setpoint input device, sensor, controller and actuator. X denotes the sampling variants, which can appear in the following sequence: ALi-ALs-CLs–PLc–ALc–CA–CLc. The hyphen „–“ means that the loop elements are connected over the network, otherwise the loop elements are realized in the same node. If the sampling variant is irrelevant then may be left unspecified (X).

The input device may be omitted in some situations, since it is realized mostly in an event-based way. However, the type of connection of the input device influences the communication delay between input device and controller. Different combinations are possible, as the examples in Fig. 5 demonstrate. Some combinations are not reasonable. For example, the configuration SP-AD-CAD-PID-I-A does not ensure that the control loop is closed in all time moments [3].

TABLE II. LIST OF IMPLEMENTED MODELS FOR WIRELESS NETWORKS WITHIN CANDY SITE FINDER [6 – 9]

Model/ Algorithm	Supported network type	Description	Used model and parameters	Category	Complexity
Free Space (FS)	WLAN 802.11, WSN 802.15.4, WiMAX 802.16, i/o	E, no consideration of obstacles	M=M(d,F,L), L=a/RF²	P	O(N)
Link Budget (LB)	the same	Determines signal power and data rates	M=M(PRx, PTx, L), DR=DR(PRx)	P	O(N)
Multi Wall Model (MWM)	WLAN 802.11, WSN 802.15.4, i	SE, regards for wall material	M=M(d,f,Material,SL)	P, in part D	O(N)
COST Walfish-Ikegami Model	WiMAX 802.16, o	SE, regards for buildings and their height	M=M(d,f,b,w,HTx, HRx,hr,a,S) F=0.8-2GHz, d<5km	P, D	O(N)
LOS visualization	WLAN 802.11, WSN 802.15.4, WiMAX 802.16, i/o	RO, regards for walls and buildings	M=M(d)	P, in part D	O(N)
Dominant Path Prediction (DPP)	WSN 802.15.4, WiMAX 802.16, i/o (also parallelized algorithms [9])	RO, regards for buildings and multiple interactions	M=M(d,f,tree)	P, D	under O(exp(N))
Extended Site Finder Algorithm (ESFA)	WLAN 802.11, WSN 802.15.4, WiMAX 802.16, i/o	AP/BS placement on the basis of signal power, „greedy heuristics“ (add/drop)	M=M(PRx,Geometry, Nap) DR=DR(PRx)	P	O(N²)
LOS Site Finder (LOS SF)	WiMAX 802.16, o	RO, AP/BS placement on the basis of LOS coverage	M=M(d,PRx,DR)	P, V	O(N)
i…indoor, o…outdoor, d…distance between sender and receiver, f…frequency, SL…cutting length „ray-to-wall“, b…distance between buildings, w…width of the street, HTx…transmitter height, HRx…receiver height, hr…building height, a…cutting angle „ray-to-roof edge“, S…city type, tree…tree representation of dominant paths, Tx…transmitter, Rx…receiver, PTx…transmitter power, PRx…receiver power, R…cell radius, Nap…number of access points, Nuser…number of users, k…number of cells in the cluster, N…general wireless node quantity, D…diffraction, P…propagation of EM waves, E…empirical, SE…semi empirical, FM…frequency management, RO…ray optical, L…user load distribution, V…visualization					

The introduced generic model is intended to present the different implementation variants for event-based controls in an explicit and structured way. During design, the engineer may use this model combined with theoretical approaches. At the end, the simulations may be used as an appropriate instrument to validate the design, see for example [2, 3]. The classification of sampling elements is not complete and should be extended as far as new methods are developed. Also investigation of new configurations created by combination of the sampling of the proposed general scheme may be reasonable. In other words, the proposed scheme can be used as a construction kit for further methods.

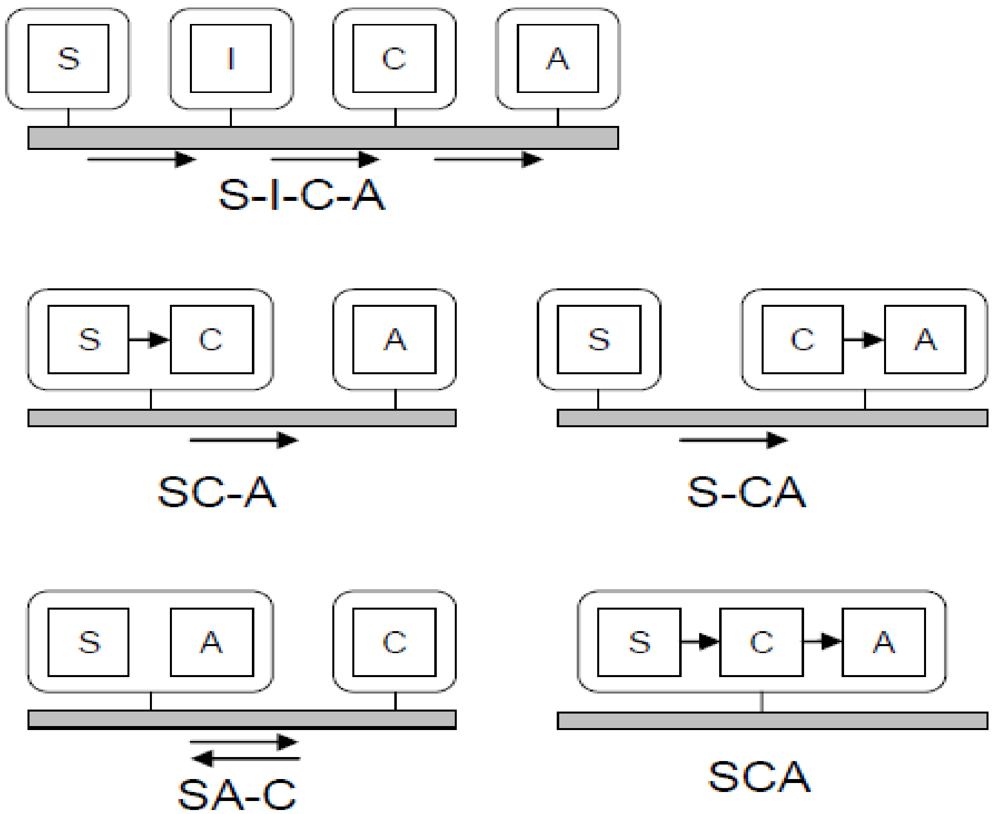

Figure 5 - Examples of connection configurations

V. CONCLUSIONS

Energy efficiency is a critical aspect for further deployment of WSN in mid-term. Its main objectives include long lifetime and reliable network with higher availability.

In the frame of the paper, the known methods for energy efficient use within WSN have been discussed. The combined approaches are demonstrated, which support cross-layer design of WSN under considering of important tradeoffs between multiple contradictory factors of efficiency.

The relevant planning tools modeling signal propagation have been discussed. The functionality of CANDY Site Finder for design of optimal topology for WSN under considering of transmitted and received power, ranges and frequencies, propagation environments (in-/out-door) as well as obstacles is generally satisfied. As a practical issue a significant scenario for an in-door monitoring area (automated room) with use of WSN planning tool CSF has been examined.

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