Business Model Assessment of Green Wireless Sensor Ecosystems

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***Abstract*— This paper analyses the technical, economic and business impacts of two novel mechanisms in energy efficient and self-growing sensor networks. The mechanisms, (1) Non Intrusive Data Aggregation (that reduces network traffic by combining separate data packets into one) and (2) Network Collaboration (that reduces traffic by resource sharing of co-located networks), are first analysed in terms of their energy saving potential. These technical gains are then translated into reduction in operational expenses resulting from longer battery life (battery costs and less human intervention in replacing batteries). However, the strength of these impacts depends on the choice of business model configuration employed. Therefore this paper, along with quantitative impacts, also includes an in-depth analysis of critical business model parameters for possible disjunctions and synergies between the key stakeholders.**

Keywords - Business Models; Impact Assessment; Wireless Sensor Networks; Energy Efficiency

I. INTRODUCTION

Energy aware technologies have already found their way into commercial networking products and offerings. From a strategic point of view, it has been debated whether to promote an "off the shelf" (Operator Independent) business model for these technologies or to support an Operator Centric business model where both long-term success and return on investments are likely guaranteed. In order to assess the impacts of engaging in either Operator Centric or Operator Independent strategy we refer to and elaborate on (in Section II) a set of energy aware and self-growing mechanisms currently being developed in the CONSERN project [2]. The project aims at developing a novel paradigm for dedicated, purpose-driven small-scale wireless networks with special focus on energy-aware self-growing systems that promise improvements in terms of operational cost, product reliability, sustainability, and increased lifetime of wireless elements. Also introduced (in Section II) is a business-model framework used to identify these mechanism-specific impacts by examining the opportunities they create and the bottlenecks that could prevent them from being commercially deployed.

Following a technical overview of the wireless sensor ecosystem (Section III), the two mechanisms are showcased (in Section IV and Section V) where CONSERN functionalities act in tandem to produce technical and economic benefits for the stakeholders active in the ecosystem. These mechanism-specific impact assessments form the basis for an analysis (in Section VI), where the mechanisms are taken together (in what could be considered a step towards a prototype of a CONSERN product) and the synergies and disjunctions between them are analysed using the business-model framework that was introduced in Section II. Section VII concludes the paper.

II. BUSINESS ECOSYSTEM DESIGN FOR WIRELESS SENSOR SYSTEMS

Currently, wireless network development is driven by horizontal mass-markets ("one size fits all"), whereas vertical markets and niche applications call for (costly) dedicated configurations or developments. The choice of business models for such systems is greatly dependent on the preferences and priorities of business stakeholders involved. These business models (derived heavily from [3]) can further be used to highlight the value proposition inherent in the systems operating under various value and control constraints. The two key variations in business model configurations for green wireless sensor networks are:

- Operator Centric Business Model (OC-BM)
- Operator Independent Business Model (OI-BM)

Figure **1** combines the two business model configurations where either a Network Operator or a Facility Owner is solely responsible for building and operating a CONSERN-like ecosystem. Operator Centric Business Model (on left in green) is a "business as usual" scenario where Network Operators choose to deploy the infrastructure and possess relevant skills to operate it. In terms of revenue flow and control, the Network Operator being the focal actor intermediates the flow of revenue and services i.e., the Network Operator chooses to internally negotiate and pay the Device Manufacturers and Service Providers for the purchase of equipment and services respectively.

On the contrary, the Operator Independent model represents the case where the Facility Owner (like airports, hotels etc.) chooses to build and operate the CONSERN ecosystem. The Facility Owner makes use of "off-the-shelf" products and deploys them independently or with help of 3rd Party Integrators.

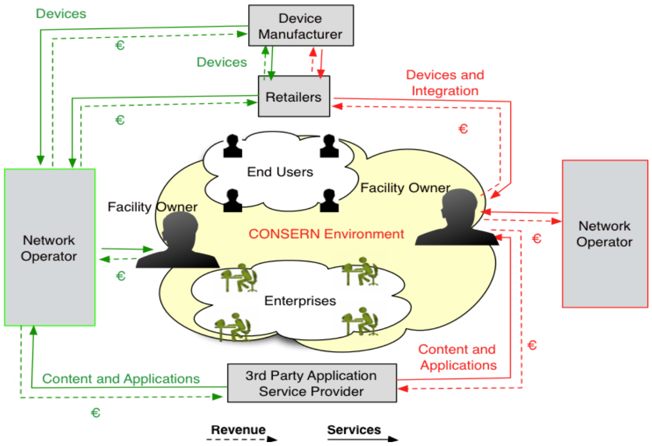

Figure 1 Operator Centric (Left-Green) and Operator Independent (Right-Red) Business Models

In place of an incumbent operator, the Facility Owner interacts directly with Device Manufacturers (through Retailers) and the Service Providers for provisioning components and services. The key motivation for developing an alternative Operator Independent business model is the fact that it explicitly captures the underlying need to deliver significant and specific impact on end users that do not have the resources to set up complex networks and which are especially benefiting from power efficient, easily scalable solutions.

A. *Framework for Business Impact Assessment*

While there are many proposed frameworks in the literature for analysing the business models, see e.g. [8] and [9], the key business model parameters related to control and value creation within the value network are best captured in the business model ontology [7]. Given the specificity of the technology under evaluation, we adapted the business model parameters from [7] in order to match the requirements and constraints posed by energy aware self-growing business ecosystems. Table **1** below explains each business model parameter in detail:

Key Value Proposition
The basic attribute that the product/service possesses which constitute the intended value to be delivered to the customer
Dependencies and Control
Refers to the distribution of processing power, control and management of functionality across the system in order to deliver a specific application or service
Partnerships
Strategic combination of resources that are available and useful in any activities a stakeholder undertakes in pursuing its goals
Know-how
Points to the possession of critical skills and resources in order to deliver the key value proposition of the service or product
Product Bundling
Refers to the complementarity and substitutability between products and services
Legacy
Related with the ability of systems to directly exchange information and services with other systems, and to the interworking of services and products originating from different sources
Deployment
Refers to issues and attributes attached to basic deployments and operations of such systems
Customer Segments
Differentiates the type of customer base that interacts in the ecosystem

Table 1: Business Model Parameters

Using each business model parameter in Table **1**, an in-depth business model impact assessment originating from the trade-offs and benefits of engaging in the two business models was conducted (Section VI). In order to further strengthen our analysis, we crosschecked and verified our findings through multiple rounds of feedbacks and validations with stakeholders active in the CONSERN ecosystem.

III. Technical Overview of Wireless Sensor Ecosystem

Energy efficient solutions represent attractive business cases by offering significant benefits in terms of operational cost, long-term product reliability, sustainability, and increased lifetime. Energy efficiency is one of the main objectives of CONSERN project. Different mechanisms for energy optimization at the terminal level, system level and network level are developed and evaluated. In this paper we choose just two of these technical solutions, and focus on assessing their potential business impact.

The pertinent network environment is identified (see Figure 2) as multi-domain, heterogeneous, dense home/office environment where different network services and capabilities are provided by different service providers and network infrastructures. In essence, CONSERN introduces new processing and communication schemes within this network environment to enable power efficient interworking of different network devices featuring: 1) Knowledge Base for network state, events, and actions; 2) Decision Making; 3) Self-growing; 4) Cooperation; 5) Autonomic Control; 6) Monitoring; 7) Execution; and 8) Translation of abstract configuration commands into vendor/hardware specific configurations. For estimating the potential energy gains accrued by solutions proposed in CONSERN, mechanisms were implemented in the w-iLab.t wireless network testbed of IBBT [5] deployed in an office building of 18x90m and spread out over three floors. Consisting of 200 nodes, each node comprises a wireless sensor node (instantiated by a Tmote Sky mote) and a custom designed hardware board that can measure its power consumption.

For the purpose of this paper, we do not perform direct power consumption measurements, rather, we measure the average data traffic in the testbed, and then calculate respective typical power consumption and lifetime values. Power saving in wireless sensors is achieved mainly by restoring the radio unit into low-power sleep-mode. Common MAC protocols for wireless sensors intelligently switch the radio on and off, to increase the amount of time it is off.

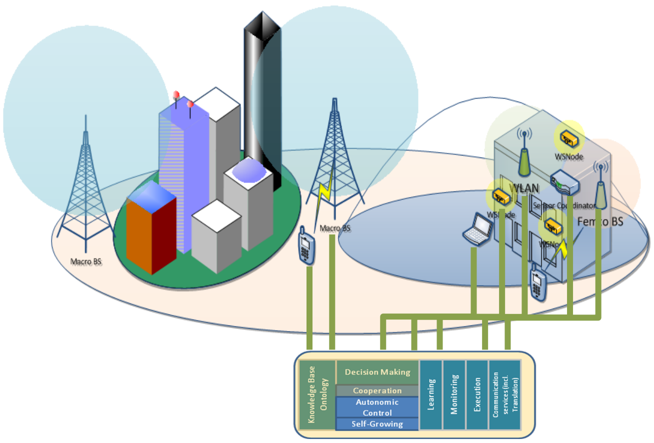

Figure 2 CONSERN's networking environment realising CONSERN functionality

Obviously, this time is limited by the traffic load in the network. For calculating power consumption, we suppose the real-life wireless sensors would employ S-MAC – one of the popular MAC protocols for wireless sensor nodes – and estimate the resulting power consumption for a typical wireless sensor node according to Table **2**, which is derived from [4]. For calculating estimated lifetime, we assume a typical situation, where each sensor node is powered by two AA batteries, with a total energy content of 30760 Joules [6].

Average Throughput (bps)	Power Rating with S-MAC Protocol (mW)
25	4
50	7.5
75	11.5
100	15
150	23
200	31

Table 2 Power consumption for S-MAC protocol

As mentioned, we focus in this paper on two of the mechanisms that were developed within CONSERN project:

- Non Intrusive Data Aggregation, which reduces network traffic by combining separate data packets into one,
- Network Collaboration, which reduces traffic by resource sharing of co-located networks.

The following paragraphs present the two mechanisms in more detail and provide technical basis for conducting business impact assessment.

IV. NON INTRUSIVE AGGREGATION MECHANISM

The non-intrusive aggregation mechanism is geared towards consolidating multiple packets into one single packet, independently of underlying protocol and information sources. A key value proposition of this mechanism is to achieve power savings by reducing the number of packet transmissions. Packet aggregation is known in the literature, but it typically depends on underlying protocols and applications. The new aggregation mechanism introduced in CONSERN is non-intrusive in the sense that it is independent of such information. It is actively operating as an intermediate layer between the MAC and network layers of the sensor node, independently and transparently to higher layers such as the application, the networking layer or the MAC. Non Intrusive Aggregation was introduced and described in detail in [10]. Its principle of operation is as follows:

- For each incoming packet arriving at the wireless interface, the new intermediate layer first extracts all information elements that are destined for this node. These information elements (parameters) are delivered to registered higher layer protocols and applications.
- If there are remaining information elements in the packet, the routing protocol processes it and sets its next hop address.
- Information elements that are waiting to be sent are examined to find those thata are destined to the final destination or the next hop of this packet. Such information elements are added to the payload of the packet before it is transmitted (relayed) to the next hop node.

For the evaluation and impact assessment purpose five different aggregation mechanisms were compared [10]:

No aggregation: The baseline scenario.

Packet combination: This is the most commonly used aggregation mechanism for Wi-Fi networks. Locally generated packets are delayed for a short time at the MAC or PHY layer before they are sent over the wireless network. If multiple packets to the same next hop address are delayed in this way, they are combined in a single MAC or PHY frame.

Traditional data-aggregation: This is the most common aggregation mechanism for wireless sensor networks. Each application generates information, which is encapsulated in a packet. In intermediate nodes, the packet is offered to the same application, that can choose to add its own information into the same packet before it is forwarded. Data packets of different applications are not aggregated together.

Joint-application data-aggregation: With this approach all applications are jointly designed. The result is similar to traditional data-aggregation, but the resulting application can combine data packets from all original applications.

Global aggregation: This is our non-intrusive Aggregation. Although applications are not jointly designed, their data is transparently combined, as if using joint-application data-aggregation.

The results of our experimental comparison are shown in Figure **3**. For each of the mechanisms we measure the average number of packet transmissions per minute per node in the same scenario, where the intervals between data and control packets are fixed (60 sec.), the tolerance to packet delay is fixed (30 sec.), and the network size is varied from half a floor (40 nodes) to three floors (about 200 nodes).

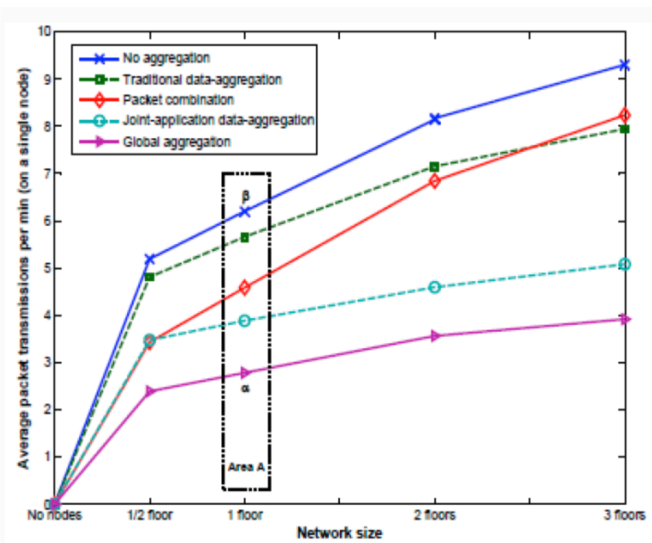

Figure 3 Aggregation Benefits in relation to network size

A. *Impact on Power Consumption*

As demonstrated in Figure **3**, using the non-intrusive aggregation mechanism can reduce the number of packet transmissions (and resulting average throughput) by more than 50%. Assuming the average size of each packet to be 100 bytes, the average throughput per node per second is calculated as follows:

$$Throughput = \frac{(Packet\ Size) \times (T_X)}{60} \quad [1]$$

where, Tx is average number of packet transmissions per node per minute. Using the power ratings from Table **2**, and interpolating it using a second-degree polynomial regression we can now estimate the expected energy savings for each of the sensor nodes. The results are summarized in Table **3**.

Size (N)	No Aggregation		Global Aggregation		% Gains per node
	Tx/node	P/node (mW)	Tx/node	P/node (mW)	
40	5.3	10.9	2.5	5.2	52.29
65	6.2	11.75	2.8	5.5	53.1
130	8.2	16.5	3.5	7.3	55.7
200	9.4	19	4	7.6	60.0

Table 3 Average energy consumption per node

B. *Impact on Battery Life*

As mentioned in Section III, we assume each sensor node is powered by two AA batteries, with a total energy content of 30760 Joules [6]. Also, given that the experiments conducted are in an in-door environment, the self-depletion of the 2AA batteries are almost negligible. Using the power consumption estimates from Table **3**, we calculate the estimated battery lifetime, as follows:

$$Avg\ Power\ (W) = \frac{Energy\ Content\ of\ 2AA\ (in\ Joules)}{Time\ (in\ Seconds)} \quad [2]$$

The results are presented in Table **4** below.

Size (N)	No Aggregation		Global Aggregation		% Gains per node
	P/node (mW)	Baseline (Hours)	P/node (mW)	Expected (Hours)	
40	10.9	784.4	5.2	1664.2	112.1
65	11.75	729.6	5.5	1554.5	113.6
130	16.5	518.1	7.3	1171.2	126.0
200	19	450.0	7.6	1125.0	150.0

Table 4 Average time of operation using 2AA batteries

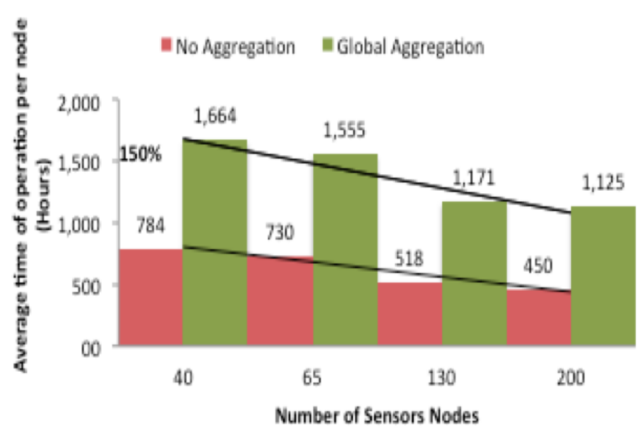

Figure 4 Baseline vs Expected impact on battery life

C. *Impact on OpEx: Human Intervention and Energy Costs*

As shown in Figure **4**, the average time of operation per node increases more than 150% with the non-intrusive aggregation mechanism. In terms of battery life, what used to last 763 hours for 2 AA batteries now extends up to 1900 hours. With increasing battery life, the frequency of their replacement goes down as well. In order to assess the economical gains due to reduced human intervention, we consider the baseline scenario where we assume it takes a team of two ICT-skilled technicians a full day to change all the batteries of a network equipped with 40 sensor nodes. Economic impact in this case is directly related to the savings achieved in the form of extended battery life. Upon scaling the network (in terms of number of sensors), the gains resulting from this mechanism are more pronounced. Table **5** summarizes the overall opex gains accrued by reduced human intervention and battery costs.

V. NETWORK COLLABORATION MECHANISM

Network Collaboration is a mechanism that allows independent networks to profit from sharing information, resources and infrastructure with each other. By sharing (network) resources and optimizing resources across network boundaries, network performance and power consumption can be optimized in a global way.

In the new network collaboration mechanism introduced in CONSERN each network has a set of well-defined incentives, or goals, e.g. `minimize battery consumption' or 'maximize throughput'. It also has a set of network services it supports, that can help realize such goals, e.g. 'shared routing' and 'packet aggregation'. Network Collaboration is achieved by exchanging information between networks, and negotiating which network services to activate in each of the networks. The experimental configuration that is implemented in the w-iLab.t testbed consists of two networks, as shown in Figure **5**.

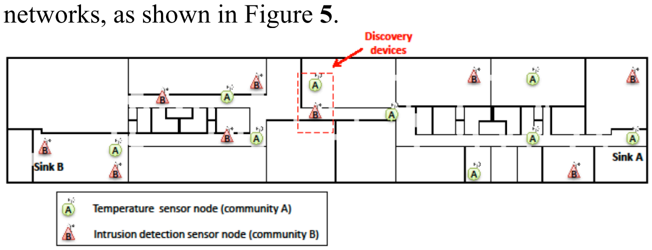

Figure 5 Network Setup of Network Collaboration

One network represents battery-powered temperature sensing nodes, with the goal of maximizing battery life; the other highly reliable intrusion detection security nodes, with the goal of maximizing reliability. The supported network services are 'packet sharing' – which allows the two networks to behave as one for the purpose of packet routing; and the non-intrusive aggregation of Section IV. The transmission power of the sensor nodes is set at -15 dBm. For routing we use the Ad hoc On-Demand Distance Vector (AODV) protocol, due to its capability to create arbitrary peer-to-peer routes, which are necessary for the Network Collaboration mechanism, and are much less suitable for more efficient routing protocols such as the Collection Tree Protocol. Nevertheless, the disadvantages of AODV are relatively less significant in wireless sensor networks, where the overall traffic load is very low. With these settings, packets require up to 4 hops to arrive from one side of the building to the other.

In order to assess the impact of network collaboration on the number of transmissions per node, we measured the performance of both networks (A and B) in four different situations [11]:

- Without cooperation
- With aggregation active in both networks
- With packet sharing active in both networks
- With optimal service selection after negotiation (packet sharing active in A and B, aggregation active in A)

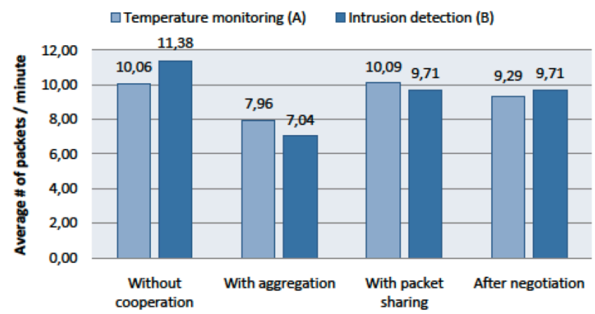

Figure **6** Reduced transmissions due to NC

Note that although both services decrease the number of packet transmissions, the result after negotiation (when both services are active at the same time in network A) is higher than when aggregation is the only active service. The reason is that the routing paths are shorter, and therefore there are fewer opportunities to aggregate packets. We can conclude that in situations where the only incentive is `maximize network lifetime', aggregation should not be activated together with packet sharing. As shown in Figure 6, network sharing can reduce the number of packet transmissions (and resulting average throughput) for Network B (and not for Network A). Using the power ratings from Table **2**, an estimation of energy savings for each of these sensor nodes can be derived. Assuming again that the average packet size is 100 bytes, the average throughput per node per second is calculated using equation [1], and with power ratings from Table 2, the expected energy savings for each of the sensor nodes is determined. The results are summarized in Table **8.**

A. *Impact on Battery life*

We follow the similar step-by-step approach (in equation [2]) to calculate the impact on battery life.

Network Size (N)	No Aggregation		Global Aggregation		Batt. Saved per Year	Batt. Savings (€) per Year	Manday Savings (€) per Year	Overall Savings (€) per Year
	Baseline Time of Operation (Hours)	Batt. Used per Year	Expected Time of Operation (Hours)	Batt. Used per Year				
40	784.4	893	1664.2	421	472	944	2360	3304
65	729.6	1560	1554.5	732	828	1656	4140	5796
130	518.1	4396	1171.2	1945	2451	4902	12260	17162
200	450.0	7787	1125.0	3115	4672	9344	23360	32704

Table 5 OpEx Savings due to Non-Intrusive Aggregation

The resulting average power consumption per node is shown in Figure 7, where the red bars are without cooperation and the green ones with packet sharing. The resulting extention of battery life is shown in Table **6**.

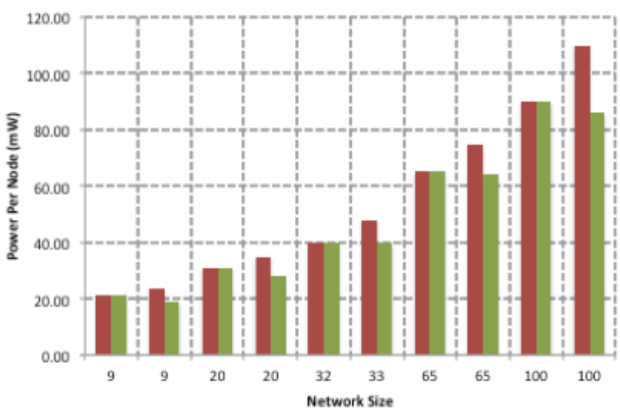

Figure 7: Impact on Power per node (A and B)

Type	# of Nodes	Battery Life (W/o Coop)	Battery Life (W/ Pkt Sharing)	Gain
A	9	407,14	407,14	0%
B	9	363,83	450,00	24%
A	20	275,81	275,81	0%
B	20	244,29	305,36	25%
A	100	95,00	95,00	0%
B	100	77,73	99,42	28%

Table 6: Impact on battery life (Network collaboration)

The results are also shown in Figure **8**.

B. *Impact on OpEx: Human Intervention and Energy Costs*

Analogously to the previous mechanism, we can now calculate the OpEx savings that follows from reduced human intervention and battery savings. These are summarized Table **7**.

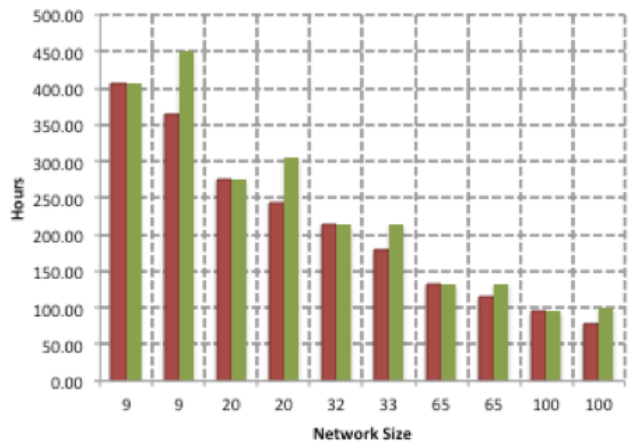

Figure 8: Battery Life extension for Network A and B

Type	# Nodes	Battery savings (€) per year	Man-day savings (€) per year	Overall savings (€)
A	20	0	0	0
B	20	573	1434	2008
A	100	0	0	0
B	100	10009	25023	35033

Table 7 OpEx Savings due to Network Collaboration

As can be seen in the table, while savings are roughly at the same relative level (25% and 28%), in absolute terms savings increase dramatically with increased network size.

VI. BUSINESS MODEL IMPACTS

In this section we synthesize each mechanism-specific business impact indicating implications for key stakeholders like Network Operators, Facility Owners in CONSERN-like business ecosystem. Using each business model parameter in Table **1**, a business model analysis is performed to qualitatively estimate the intensity of impacts originating from the trade-offs and benefits of engaging in the two business models. Impacts from both mechanisms are presented together in the table.

A. *Impact on Power Consumption*

Type	# of Nodes	Without cooperation: Transmissions (Tx/node/min)	Without cooperation: Throughput (bps)	Without cooperation: Power/node (mW)	With packet sharing: Transmissions (Tx/node/min)	With packet sharing: Throughput (bps)	With packet sharing: Power/node (mW)	Gain (%)
A	9	10,06	134,13	21,00	10,09	134,53	21,0	0%
B	9	11,38	151,73	23,50	9,71	129,47	19,0	19%
A	20	15,00	199,95	31	15,04	200,55	31	0%
B	20	16,96	226,19	35	14,47	193,00	28	20%
A	100	33,53	447,11	90	33,63	448,44	90	0%
B	100	37,93	505,78	110	32,37	431,56	86	22%

Table 8 Power gains per node with Network Collaboration

	Business Model Impacts
Key Value Proposition	Substantial savings are generated. For example for a 200 node sensor network (or two separate 100 nodes networks in the case of network collaboration), average power consumption per node can decrease by 50% and 11% (22% /2) for Non-intrusive and Packet Sharing Mechanisms respectively. Extended battery life by 150% and 14% (28% /2) will trigger gains e.g. reduced human intervention. However, the value proposition of the mechanisms varies considerably depending on the choice of batteries used. For instance, replacing 2AA batteries with high capacity/rechargeable batteries could alter the overall replacement and purchase costs for a given network deployment.
Dependencies	Both mechanisms emphasize distribution of intelligence amongst the nodes, where each node aggregates the payload and transmits without having any direct impact on the service or purpose. It is to be noted that aggregation and packet sharing fails on the ground of reduced reliability and privacy issues thereby delimiting the range of services/applications it can be deployed for.
Partnerships	The non-intrusive mechanism lacks the inter-domain attributes and operates only on the sensor nodes irrespective of the ownership; hence the gains achieved using the mechanism will be equally distributed to the business actors involved. On the contrary the Network Sharing mechanism will be true in reality when two networks cooperate and share with each other, two imminent barriers are foreseen: 1) Operator has to initiate and achieve inter-operator agreement (not likely) 2) The facility owner has to achieve inter-operator agreement (very difficult)
Know-how	Both mechanisms allow the sensor nodes to aggregate packets automatically without human intervention
Product Bundling	Integration and success for such mechanisms highly depend on standardization of CONSERN functionalities. Usually the bigger the organization, like service Operator, the greater is the push for standardizing the solution.
Legacy	Applied using a software upgrade in the sensor nodes (Tmote sky sensors) the mechanism is equally compatible with existing legacy and networking elements.
Deployment	Higher chances of success if an Operator is employed to deploy the sensor nodes (economies of scale) whereas for "Do it yourself" model, the impact of increased battery life and reduced human intervention will be further diluted.
Customer Segments	Both mechanisms primarily target Home/office environment. However other segments are possible to address (e.g. Campus Environment). Expanding into other customer segments has the potential to substantially increase the positive impacts.

Table 9 Operationalization of BM parameters

The business model impact assessment suggests a good fit for several of the parameters. The key value proposition is attractive for both business models; deployment is easily made via software upgrades, and mechanisms function without human intervention. However, for the network collaboration mechanism, independent networks need to collaborate. Unless the same actor manages both networks, this has to be achieved through inter-operator agreements, which will be difficult to realise. The analysis also shows that larger operators have better possibilities to realize economies of scale and influence standardization, which in turn will increase the chances of a successful CONSERN deployment.

VII. Conclusions and Future Work

This paper evaluated two energy efficient mechanisms currently being researched and developed in the FP7 Project CONSERN [2]. An in-depth analysis of the two mechanisms demonstrated them as promising paths towards achieving substantially greener and cost-effective ecosystems. In Table **10**, we cross-compare the two mechanisms in terms of overall costs and reduced human intervention led-savings. For example, for a 200 node network, cost savings of more than 30000 € could be achieved for each of the mechanisms taken individually.

	Non Intrusive Aggregation Mechanism			Network Collaboration Mechanism		
# Nodes	Battery savings (€) per year	Man-day savings (€) per year	Overall savings (€)	Battery savings (€) per year	Man-day savings (€) per year	Overall savings (€)
40	944	2360	3304	573	1434	2008
200	9334	23360	32704	10009	25023	35033

Table 10 Cross Comparison in terms of savings due to Intrusive Aggregation and Network Collaboration Mechanism

However, for smaller network deployments, the non-intrusive mechanism seems to be more cost effective. It is to be noted that these costs estimations are derived for a given network set-up furnished with 2AA batteries, however using high-power/rechargeable batteries like IEC R20 would alter the overall battery lifetime and hence replacement and purchase costs. Further research is needed to determine how sensitive these cost calculations are, and how these savings would add up when these mechanisms are applied in an integrated *"CONSERN-box"* like product.

Even after achieving high technical and economic gains from the mechanisms, also the choice of the business model (Operator Centric or Operator Independent) will determine the long-term viability of the CONSERN product and its ecosystem. We found a good fit for both mechanisms and business models, for several parameters. However, some fundamental strategic disjunctions between the objectives of the Network Operator and that of the Facility Owner were identified. In particular, unless the same actor manages both networks, network collaboration will be difficult to realise. Unless this barrier is addressed adequately such disjunctions might prevent CONSERN from being deployed. It seems therefore questionable to integrate both mechanisms into the same product offering.

The most urgent avenue for future research and development is to analyse other CONSERN related mechanisms currently being researched in order to establish which are the business related synergies and incompatibilities. One or several integrated product offerings could then be proposed. This implies further methodological development when it comes to combining separate business model analyses into an integrative analysis, as well as for linking the analysis of technical and economic impacts to a business model impact analysis.

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AUTHOR BIOGRAPHIES

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