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A comparison of different technologies for EFC and other ITS applications

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Abstract— Microwave has been up to know the preferred technology for Electronic Fee Collection (EFC). In the last years new technologies came to EFC arena: infrared and location satellite based systems plus cellular networks. This paper tries to present these technologies and a comparison not only based on performance but also cost-effective.

Index Terms— ITS, EFC, tolling, radio frequency, microwave, infrared, positioning systems, cellular systems

I. INTRODUCTION

In the early 1990's, the first EFC systems were installed, coming from different manufacturers and road operators. Each one did his job, and interoperability wasn' t seen as a primary requirement. The first devices were DSRC (Dedicated Short Range Communications) devices which operated at 915MHz (LMS-Location and Monitoring Services band) or 2.45GHz (ISM-Industrial Scientific Medical band). Although these were mainly the only frequency used, each manufacturer developed his own communication protocols and applications. As a result, different and incompatible systems appeared, many times using the same frequency carriers, which made even difficult to install two tags in the same vehicle as one would interfere the other.

Later, users began to demand a continuous service when driving from one toll motorway to another, and also interoperability was seen as a market benefit, since manufacturing costs would be reduced if a standard applied and mass manufacturing became possible.

So the standardization bodies started to work on a standard for EFC. In the USA the 915MHz band was chosen for their standard, while CEN chose 5.8GHz, because the European GSM standard was operating at the 900MHz band and interference would be expected. In Japan, ARIB (Association of Radio Industry and Businesses) came up with a standard at 5.8GHz too, but not being interoperable with the European one. The FCC also proposed the allocation of a 75 MHz wide band, between 5.85 and 5.925GHz, reserved for the use of ITS DSRC devices.

At least now there is an standard for each region in the world, one could think. But the discussion doesn' t finish here. These systems have some problems with interference from other devices, and frequency allocation is not uniform in all countries. Also, affecting to this frequency bands, is the problem of the metal coated windscreens, which will be further discussed in this article.

At the same time, EFC systems based on other technologies have appeared, claiming for a place in this market. These include mainly DSRC-Infrared technology and GNSS/CN (Global Navigation Satellite System / Cellular Network). The manufacturers talk about great enhancements in the performance of an EFC system using their technologies, and new standards have been proposed for the Physical Layer of DSRC.

The question is: ¿which is the best technology for EFC? or ¿which one would be the more suitable for the conditions of an specific road or country? This will depend not only on the existing toll road configuration but also on the performance of the considered EFC system.

In this paper we will show the characteristics of the available technologies for EFC, trying to make some comparisons from a performance point of view.

Further in this paper it will be considered RF (Radio Frequency) technologies as the ones which make use of bandwidth below 1GHz, and MW (Microwave) technologies as the ones which operate at frequencies between 1 and 300GHz. IR (Infrared) technologies will designate devices operating in the infrared spectrum (between microwaves and visible light) and GNSS/CN technologies will designate vehicle positioning systems which make use of satellite infrastructure and cellular network for communications.

The term DSRC refers to short range communications between a beacon or RSE (Road Side Equipment) and a tag or OBE (On Board Equipment).

In the following sections it will be discussed the characteristics of each considered technology.

II. CHARACTERISTICS

A. RF Technologies

If we search a definition for radio frequency, it will be something like "*the portion of the electromagnetic spectrum that is between 3kHz and 300GHz*". In this paper

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we will consider RF as the part between 3kHz and 1GHz only, to make a difference between RF and MW systems.

Radio frequency waves are radiated waves that belong to the lower part of the spectrum. We will considerate RF spectrum as the frequencies from 0 to 1GHz. DSRC tags operating at RF spectrum usually make use of the 915MHz LMS band.

RF tags can transmit through walls and solid objects. Non-line of sight communication is possible although transmission losses are higher in this case. RF cannot penetrate metals. A car has a lot of metal parts. Therefore, communication must be through the glass, or by means of an external antenna. The first option is commonly accepted and so the tags are mounted behind the windscreen. There is a problem with metal-coated windscreens, because the signal suffers big attenuation up to 40dB when crossing the glass. The European DELTA [1] project (DSRC ELectronics implementation for Transportation and Automotive applications) is working on that subject, and proposed solutions include at short time maintaining a hole or window in the metal coat, and integration of the DSRC OBE in the vehicle at long-medium term. However, these doesn't give a solution to the cars currently equipped with metal-coated glasses.

RF tags can be active or passive. Passive tags modulate and reflect the received power from the RSE. This is called backscatter transmission. Passive tags are read only, simple and cheap tags which are designed for a single application like tolling. Active tags are battery powered and can be read/write tags, more expensive but also more complex. The more complex version of a OBE integrates an smartcard. A smartcard is an intelligent electronic card, with integrated microprocessor and a communication link (which can be contactless) to the OBE. Smartcards provide flexibility, as they can be used for other applications like public transport when not inserted into the OBE, and can also hold a prepaid account.

RF tags can operate in half-duplex or full-duplex mode. If the same frequency is be used by the OBU and the RSE, communications must be half-duplex, to avoid interference between them. Full duplex communication is also possible, but different frequencies must be allocated for the downlink (from RSE to OBU) and for the uplink (from OBU to RSE). Passive tags can only operate in half duplex mode.

RF transmission is affected by reflections. As a coherent wave, propagation depends on amplitude and phase, and the phase varies with the distance and frequency. The received signal at any point is the result of the contributions of directed and reflected signals, with their amplitudes and phases. When these contributions have opposite phases, they cancel each other, and received signal can become zero or near to zero. This is called multipath propagation loss. A receiver moving across this fading points will find trouble to communicate. Multipath propagation losses are difficult to estimate, since they change dynamically, depending on the reflecting objets present at any time, which are the ground, buildings and vehicles.

RF interference appears when a non-desired signal is received in the receiver bandwidth. Also receivers suffer a phenomenon called inter-modulation, caused by deviations and tolerances of the components of the mixers. Nearby transmitters operating in adjacent bands can interfere to our system. For this reason, the frequency bands must be allocated with attention to the rest of existent devices that are operating in the specified frequency band.

RF is a non-ionizing radiation. Ionizing radiation, like X-Rays, when exposed to human cells can change the DNA and produce cancer. Ionizing radiation also has cumulative effect so a long term exposure is also dangerous. We don' t know very much about the effects of non-ionizing radiation on humans, but many experiments have been carried out with animals, showing that thermal as well as non-thermal effects can produce health problems, depending on the frequency, power and duration of the radiation exposure. That' s well understood with the example of the MW oven. MW oven produces thermal effects on tissues. MW oven operates at 2.4GHz, and at this frequency water particles resonate and generates heat. Each kind of tissue is excited by a different frequency, and lots of studies are being carried out to determine this effects.

There are regulations to protect public safety from radiation. These regulations limit the maximum radiated power for each frequency and application. Table 1 shows regulations for RF an MW radiation for different regions of the world [2][3][4].

Table 1
Exposure Limits for RF and MW Exposed, General Public

ICNIRP		CENELEC		ANSI / IEEE	
f(MHz)	$S(W/m^2)$ (**)	f(MHz)	$S(W/m^2)$	f(MHz)	$S(W/m^2)$
10-400	2	10-400	2	3-30	20-11
				30-100	11-0.2
				100-300	0.2
400-2000	f / 200 (*)	400-2000	f / 200	300-3000	f / 1500
2000-300000	10	2000-150000	10	3000-15000	f / 1500
		150000-300000	0.0000667·f	15000-300000	10

(*) – Frequency, f, is in MHz
(**) – S means spectral power density

B. *MW Technologies*

All the characteristics of MW are the same than for RF, with a few differences, due to the fact that MW are higher frequencies.

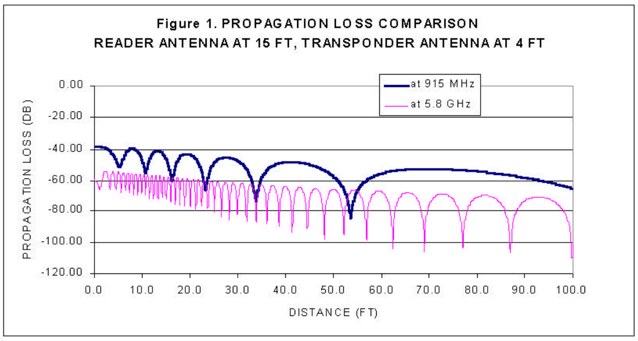
First, propagation losses are higher for MW. If a transmitter transmits P_t watts from an antenna with gain G_t, a receiver at a distance d away receives P_r from an antenna with gain G_r. In the formula, c is the speed of light and f the frequency.

$$P_r = (P_t/4?\, d^2)\, G_t\, G_r\, (c^2 / 4?\, f^2)$$

Therefore, the higher the frequency, the higher the propagation losses are in free space.

Second, attenuation due to weather conditions is also higher, as the wavelength is more similar to the size of the particles of the rain, water vapor, etc.

Third, multipath propagation losses are more unpredictable, because the phase of the signal varies more with the distance. Look at Figure 1 for comparison between RF and MW propagation loss [5]. Also, there is more bandwidth available for higher bit rate applications, and there is less electromagnetic pollution in the MW spectrum. Finally, antennas can be smaller and more directive.



As we can see, the 5.8GHz frequency band is a compromise between higher propagation loss an higher spectral noise.

C. IR Technologies

Infrared is a line-of-sight technology. That means that OBU must ' see' the RSE to communicate. Also communication is possible via reflections of the IR signal (think of the IR commander of your TV). IR signals can not go through opaque surfaces or objects. Communication must be through the glass of the windscreen. We can understand IR as a kind of light, with similar properties than the visible light.

For ITS applications incoherent infrared has been considered. This mean that the transmitted signal is not pure in frequency terms (in contrast with lasers), and has a spectral wide (commonly from 50 to 100nm). Incoherent infrared transmission doesn' t have to take account of the phase of the signals. The IR signals can be interpreted as power vectors, and the receivers sum up all power with always positive signs. This avoid any problem with multipath, and even reflected signals contribute with more power. Communication through metal coated windscreens is also possible, as attenuation are lower for the IR spectrum (up to 7dB).

IR allows very high data rate communications because the IR spectrum is placed at very high frequencies, so a lot of bandwidth is available.

Propagation loss in free space is higher than for RF an MW, and also attenuation due to weather conditions. IR is more affected by smaller particles like fog, since IR wavelength is from 1?m to approximately 1mm. However, regulations for IR emission are much less restrictive and very high power transmission is allowed not representing a risk for human health. IR is also a non-ionizing radiation, and the only known risks are related to the eye direct exposure to high power IR for a long time.

IR does not receive interference from other devices. IR is a real short range technology and few spectrum pollution is present, mainly coming from the sun light. For this reason, no allocation frequency license is required. Regulations only apply to maximum exposure limits. IR can be legally used unrestricted in any country for any application worldwide.

IR signal can be focused by optical means like lenses and mirrors to achieve well defined communication zones.

D. GNSS/CN Technologies

GNSS/CN (Global Navigation Satellite System / Cellular Network) are those systems making use of a satellite-based positioning and navigation system to compute the location of a car in a road network, the covered distance, border crossings, and all the data necessary to calculate a fee. Satellite navigation systems provide a one way signal (from the satellites to the receivers on Earth), so usually a cellular phone system is used to communicate with the control system, which performs the transaction by means of a central account of a financial entity or prepaid smart card.

These systems are becoming popular because they require the minimum infrastructure. Most EFC systems require a RSE (Road Side Equipment) to communicate with the OBU. This is the part which increases the cost of the system for the operator. Sometimes it is even very difficult to install a new toll plaza due to physical restrictions of the road. Let' s say, for instance, that we would like to set a toll plaza in a free road, where we can't allocate enough space for a stop-and-go toll facility, so a multilane freeflow system would be required (which is not actually supported for all systems and also means a problem for non-equipped users). Even more difficult is to set a toll system in an urban area. This problems are avoided by a GNSS/CN system, as no road side infrastructure is required.

The operation of a GNSS/CN is different to DSRC-based technologies. Here we talk about a "virtual gantry", as no gantry is crossed at all. Instead of charging when driving through a number of defined points of a road, GNSS/CN defines a fee for driving in a whole road network. The satellite positioning system is used to track the vehicle position through the network, and different fees can be applied depending on the selected road. In this way, the precision of the satellite positioning system is critical for the performance of the system. A user driving on a free road adjacent to a tollway must not be charged by the system. The charging information is stored in a database, which is in most cases integrated on board and has to be updated when changing the charging rates or when driving into a new network. Also the classification information of the vehicle has to be stored in the database of the OBE, because it can' t be measured on the road (it could be, but no gantries and road infrastructure are likely to be installed in a GNSS/CN system, since the main advantage of these systems is the low cost of the road side infrastructure).

The Swiss Government has launched the first large scale GPS-based project, which will be soon operable and will charge the heavy vehicles for the distance covered in all the Swiss Road Network. This system will make use of MW 5.8GHz DSRC technology for communications between the OBE and a RSE when crossing the Swiss borders, and a GPS system to compute the covered distance.

The USA and Russia provide the two navigation satellite systems now available (GPS and GLONASS respectively). A third system, Galileo, built and operated in Europe, is due to come on line between 2005-2008. The three systems will be fully interoperable, which means that a user on Earth will be able to determine a position with any receiver picking up signals from any combination of satellites belonging to any of the three systems.

Until now, the accuracy of GPS civil receivers was limited to a hundred of meters by SA (Selective Availability), a degradation of the GPS signal which was introduced on purpose by the US Government. On May 1, 2000, Bill Clinton announced that the SA degradation would be discontinued from GPS signal. Since SA was discontinued, GPS users have routinely observed horizontal accuracy values of 10-15 meters. Galileo will deliver positioning accuracy down to 4 m, by offering dual frequencies as standard, which is unprecedented for a publicly available system. Nowadays, dual frequencies are only available for military users.

Satellite navigation systems make use of spread spectrum techniques for the signal transmission. This gives protection to interference so that these systems can coexist with any other system transmitting in the same band.

A cellular phone system is used to carry out the transaction, and future cellular systems with higher bit rates could be used to remotely update the vehicle database. This transaction can be done at any moment and anywhere into the road network. This is the more powerful feature of the virtual gantry, allowing an unlimited number of vehicles to be charged, without any speed restriction since there is not a transaction time limit. Also navigation systems have unlimited capacity.

III. Comparison

A. *Signal to Noise Ratio*

SNR (Signal to Noise Ratio) is the margin between the received power of a signal and the noise level. Most modulation types require a minimum of 13dB SNR to achieve a 10^{-6} BER (Bit Error Rate).

Such a SNR has to be guaranteed with a security margin, to prevent fading and fluctuations of the signal, weather and windscreen attenuation. The calculation of this margin is called budget.

For RF and MW technologies, the maximum transmitted power allowed is strictly limited. Table 3 shows the exposure limits for different RF and MW technologies, for general public, based on ICNIRP, CENELEC and IEEE regulations shown in Table 2. Taking into account propagation loss for a communication zone of about 10m, windscreen attenuation and other security margins, we find that RF and specially MW (because propagation loss is higher) technologies are working near the noise margin. That's why a problem such as metal coated windscreen extra attenuation cannot be solved simply by increasing the transmitted power or the receiver's sensitivity. Transmitted power is near the maximum allowed, and also very sensitive receivers are being used yet.

Table 3
Exposure Limits for different RF and MW technologies

	S(W/m^2)		
Frequency	ICNIRP	CENELEC	ANSI/IEEE
915MHz	5	5	0.61
2.45GHz	10	10	1.63
5.8GHz	10	10	3.86

For passive backscatter tags propagation losses are higher, as there are two-way propagation losses, and also an attenuation produced by the reflection process.

For the IR, although propagation loss is higher, regulations for the maximum transmitted power are much less strict. The sun spectrum includes 100W/m^2 of IR power in the relevant spectrum at 850±50nm, which is clearly greater than the maximum exposure values for other technologies, and is not considered to be dangerous. The IEC 825 regulation [6] allows the emission of 100W/sr without obligation of using laser classes. Therefore, for an EFC application, if some kind of problem with attenuation appears, it is possible to increase the transmitted power because the power used for a typical EFC application is far to the power limitation. Moreover, IR tags are always active, so that only one-way propagation losses have to be taken into account.

GNSS/CN technologies can even work below the noise level because of the spread spectrum techniques being used in the modulation/demodulation of the signal. Although, in some situations, like driving through a tunnel, the receiver may have problems to "view" the 3 satellites needed for horizontal positioning.

B. Communication Zone

Communication zone is defined by the maximum range of the signal within the SNR limits. A 4-7m communication zone is normal for an EFC system with passive tags. The length of the communication zone plays an important role in the maximum driving speed achievable through the toll facility and in the throughput of the system. The longer the communication zone, the higher is the maximum speed, and more transactions can be done at the same time. Maximum speed also depends on the bit rate. Considering a transaction as a fixed number of bits, longer communication zones give more time to exchange the information between RSE and OBU, and higher bit rates allow to do this operation in a fewer time. As a result, long communication zones and high bit rates are desired for an EFC application to achieve high vehicle throughput.

Active tags allow longer communication zones, as the propagation losses are one-way. IR active technology allows longer communication zones than RF and MW. While IR communication zones can reach 100m length, RF and MW active tags allow up to 30m, and the communication zones for passive backscatter tags don' t use to be longer than 10m.

This concept is not applicable for GNSS/CN, as the communication zone is not restricted to a short range link.

C. Reuse Distance

Reuse distance is also a concept that applies only for a DSRC link. It defines the shortest distance that should separate two different gantries, avoiding interference between them.

Four different reuse distance are defined, depending on the considered source of the interference and the device receiving the interference. For example, the downlink on downlink reuse distance refers to the interference created by a second RSE (downlink) to the OBE received power (also downlink). See Table 4 for reference on the reuse distance for the different DSRC technologies. This data is extracted from standards and technical reports listed in [10][14]. Re-use distance is likely to be as short as possible, since some applications may require to set two gantries one near to the other (in urban tolling or parking facilities, for example).

Table 4
Re-use distance for different DSRC technologies

	Re-use distance	
Interference path	MW at 5.8GHz	IR at 850nm
Downlink on uplink	330m	80m
Downlink on downlink	35m	115m
Uplink on uplink	260m	Negligible
Uplink on downlink	Negligible	175m

D. Bit Rate

The bit rate is important in an EFC system to achieve a high throughput and reliability. The higher the bit rate, the shorter is the time of the transaction. With a short transaction time, a vehicle has more chances to have a successful communication, if any error occurs. High data exchange rates will also facilitate the transmission of other information such as real-time data collection and dissemination, and the integration with other ITS advanced services.

Also for some new ITS DSRC applications, high bit rate will be required. Table 5 shows current bit rate for different DSRC technologies, extracted from the current standards and technical documents. Again, bit rate is not a relevant parameter for GNSS/CN, since the transaction may be done at any time. In this way, the speed of the vehicles is not limited by a transaction time.

Table 5
Bit Rate for different DSRC technologies

Technology	Downlink	Uplink
RF at 915MHz	500kbps	500kbps
MW at 5.8GHz, CEN Standard	500kbps	250kbps
MW at 5.8GHz, Japan Standard	1024kbps	1024kbps
IR at 850nm	500kbps	125kbps

E. Interference and frequency allocation

Historically, communication systems have increased their frequency year after year. For this reason, RF spectrum is more congested than MW spectrum.

The 915MHz, 2.45GHz and 5.8GHz frequency bands are unprotected bands where the ITS DSRC devices have to co-exist with other devices transmitting in the same band, and might receive interference from them. The 915MHz LMS band is used in Europe by the GSM standard. The 2.45Ghz ISM band is used by microwave ovens, satellite transmissions and also recently by Bluetooth devices. In the 5.8GHz band interference from amateur radio operators could be suffered [7][8], as they are allowed to transmit with high power up to 1.5kW in this band, and also from military devices operating in the 5.0-6.0GHz frequency band. Some countries even don' t manage their spectrum, so interference may appear in tollways deployed near borders.

IR does not receive interference from remote IR devices, as it is a short range technology, and no allocation frequency license is required to install IR systems.

Satellite navigation system frequencies are standardized worldwide, so that there are no frequency allocation problems, and can operate in electromagnetic congested environments.

F. Standardization Level

Different standards have been developed for ITS-DSRC basically in three regions of the world: the USA, Europe and Japan.

The US standard for EFC is the ASTM V.6/PS111-98 [15] for the 915MHz band. Europe has a standard for 5.8GHz, from CEN Technical Committee 278 [10], which ISO has also accepted. The ARIB STD-T55 standard [16] also is based on MW 5.8GHz technology, but is not compatible with the CEN standard.

For the IR a standardization effort was made by CEN TC278 until 1996, which was probably stopped because there was a single supplier for EFC systems. Current IR EFC systems are based on a Internal Technical Report which resulted from this effort, the ITR N526 [14].

New proposals have recently come from CEN TC278 for development of new high-data-rate standards for the Physical Layer, using MW at 5.8GHz and IR at 850nm. Bit rates of 10Mbps are expected, with allocation of additional 10MHz for the MW band.

There is also a work group from CEN working on GNSS/CN [18]. This group addressed its task to ISO in 1998 as much interest was awaken about GNSS/CN outside Europe. The GPS [17] and GLONASS specifications are worldwide accepted and used.

G. Cost

This paper is focused on the performance of different technologies for EFC, but also a cost approximation will be done. Cost can be divided into two categories: cost for the operators and cost for the users.

Cost for the road operators come from the road side infrastructure, enforcement, operation and maintenance. In this way, GNSS/CN systems are costless, as they avoid the installation of any gantry. IR has also cheap solutions with solar powered RSE mounted on single poles and one way communication protocol (the fee is discounted from an account kept in a smartcard), and combined fixed/mobile IR enforcement.

Cost for the users depends on the complexity of the OBE. Passive tags are cheaper than active ones. MW tags are more expensive than RF tags, as demodulation circuits are more expensive for higher frequencies. IR components are cheap, but IR tags are always active. A GNSS/CN OBE is a quite expensive solution, as it integrates two different systems (positioning system and communications system). While passive tags are costless, the more complex active tags (Smartcard-based RF/MW/IR tag, GNSS/CN tag), can be seen as a more flexible solution, providing added value services to the user.

IV. Conclusions

Several technologies can be used today for an EFC application, having different properties and benefits.

Standards and interoperability issues are the key for a wide market deployment, and a careful analysis should be done to determine the best technology, which will depend on the characteristics of the road network and the user requirements not only from the drivers but also from road operators.

But, ¿does interoperability appear to be a real need? Perhaps it is not a real user need, as common users of a toll road use to do short trips, except for the case heavy lorries, which travel across the borders of different countries. However, in such a little market as for EFC, it is desirable that a common standard applies for the equipment, so that mass market deployment can be carried out, with different manufacturers competing with interoperable products.

There are still other technologies to be considered for EFC, like Bluetooth and other spread spectrum based technologies, which can offer superior noise immunity, but usually at higher cost.

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